Design and implementation of an intelligent water heater control module for feedback and demand side management

by

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Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own own original work, unless stated explicitly otherwise, and I have not submitted it previously, either in entirety or in part, for obtaining any qualification.

Date:_______________

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Abstract

The power supply infrastructure of South Africa has been unable to match the rising demand for electrical power. This has brought to light that there is a need for the existing power generation capacity to be used more effectively. A method of achieving more effective power use is the implementation of demand-side management. In order to achieve this there is a need to both facilitate residential demand side management and to collect data to determine how effective the various management methods were at reducing power consumption.

It was determined that uncontrolled water heating formed the greatest percentage of residential power use. It was assumed that greatest per-unit savings could be achieved by addressing the sector of greatest use. Therefore it was decided to design a control unit that would provide monitoring and control of an electric water heater to the user. The unit would be able to implement schedule and temperature set-point control and would also provide the user with the information required needed to encourage more cost effective, and therefore power efficient, in their behaviour. Additionally, the data would be entered into a central database for analysis and centralized control.

This unit was then designed, manufactured, tested and installed in several homes. The data received from the operational units was analysed to determine the effectiveness of the unit in accurately monitoring and controlling a domestic water heater. Overall the unit achieved its primary goals. It was able to accurately record usage data and reliably report it both to the users and to the centralized database. The temperature of the hot water cylinders was able to be controlled by means of a feedback control loop.

Finally, a noticeable change in behaviour from an established baseline was detected when users were given access to their own usage data. It is recommended that further study be done to verify the behavioural response of users to feedback.

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Chapter 1

Introduction

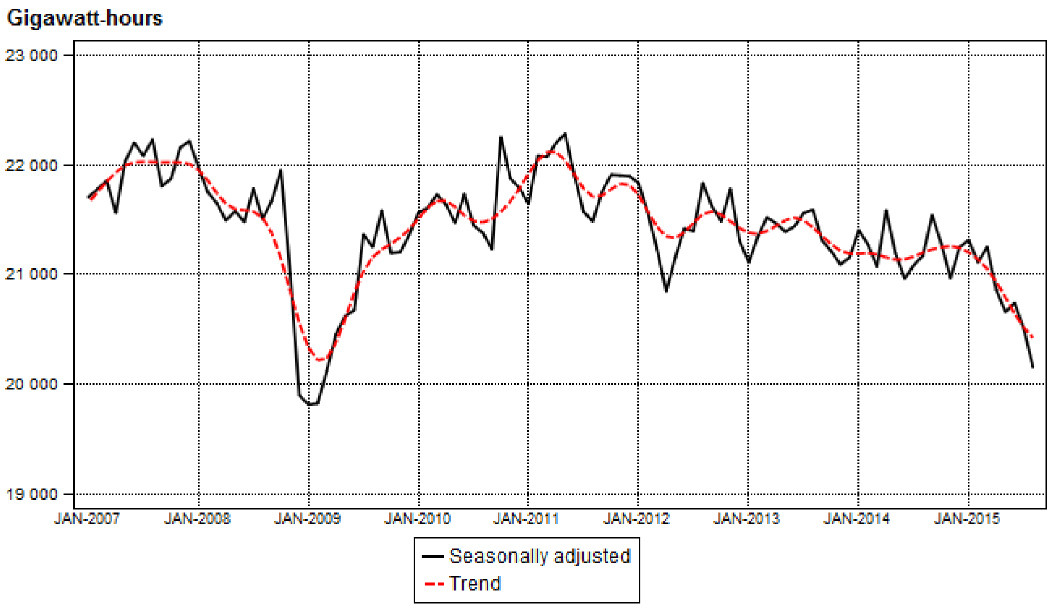
1.1 Overview

In this chapter, the current situation of power generation in South Africa will be examined. From this analysis, it will be seen that there is a need for additional measures that can be used to assist in the ongoing process of demand side management implementation. This as part of an on-going and multi-faceted approach curb the rising demand for power. A solution to this problem is then given in the form of an intelligent electric water heater (EWH). The solution is further developed as concrete objectives are formed based on the potential application of the idea.

1.2 Summary of power supply in South Africa

The power supply in South Africa is currently under stress. This is in part due to the rising demand for electricity, which is rapidly approaching generation capacity. Incidences where demand had the potential to exceed generation capacity have been evidenced in recent years by the institution of rolling blackouts, in an effort to maintain grid stability [1]. These planned power outages are a crude form of demand management in which load is shed in order to prevent a nationwide blackout. The measure of the ability of a power network to cope with additional load at any given point is known as surplus capacity. This is the additional load that the power network can support, and is given as a percentage of the current load. As of 2014, at peak load, South Africa was operating at a surplus capacity of just 8% - just over half of the typical international minimum of 15% [3]. When power generation plants are taken offline for necessary maintenance this can drop even further.

Figure 1.1: Electricity generated in South Africa [2].



This situation has resulted in Eskom, the state-owned entity that supplies 95% of all electricity in South Africa [4], having to take measures to increase the generating capacity, in order to maintain stability of the power system. These measures included the reopening of power plants that were mothballed in the 1990s, the construction of open cycle gas turbine plants, and the construction of two new power stations. Medupi and Kusile stations add a capacity of 9564MW to the national grid, an additional 21.6%[5] [6]. However all of these methods require time to implement. Returning a mothballed power station to a completely operational state takes approximately three to four years, while the construction of a new coal power station typically takes eight years [5] [6]. Both Medupi and Kusile have been delayed and are expected to be completed in 2021 [7], five years behind schedule. In fact, as shown in figure 1.1, the total electricity generated in South Africa has been decreasing since January 2011 [2].

Eskom has instituted the shorter term solution of Demand Side Management (DSM) in the interim. DSM can be summarised as reducing the demand for power through a change in consumer behaviour. This is achieved by causing the consumers to use less power by providing them with the incentive and means to do so.

The incentive is provided through the implementation of power tariff increases of 78% between 2008 and 2011 to fund the production of the aforementioned additional generation capacity. Additionally, power tariffs are set to further increase by 8% per annum [1]. Further incentive has been provided in the form of smart meters which monitor the power consumption of a household and shed the load if a power threshold is exceeded at stated times [8].

So far, means to reduce demand have included, among others, the installation of Compact Fluorescent Lights (CFLs), ripple controlled EWHs and solar water heaters in many homes and workplaces, as well as pilot schemes to reduce power use during times of peak load.

1.3 Proposed response

Applications that aid in the implementation of DSM have great potential to alleviate the situation of excess demand in the short term. This will also contribute to an increased energy efficiency. As can be seen from figure 1.2, the industrial sector accounts for 60% of the electricity consumed in South Africa. However the varied nature of that use would require the development of a solution specific to each of the many applications and the implementation of such a solution would need to avoid having an impact on the fragile economy. This would be better achieved by the in-house engineers who would already be familiar with the processes and motivated by the previously mentioned increase in electricity tariffs. For this reason it was decided to devise an aid for the residential sector, the sector which consumed the second largest amount of electricity.

As can be seen in Figure 1.3 water heating is the area of greatest electricity consumption in the residential sector. At 35% it offers the greatest opportunity for overall power usage savings and peak power use reduction [10]. As further shown in Figure 1.3, 72% of water heating has no control unit at present. The proposed solution should then directly address this 72% that does not yet have a control system. Focusing on the area of highest consumption will offer the greatest return per unit installed.

Figure 1.2: Breakdown of national electricity consumption by sector [9].

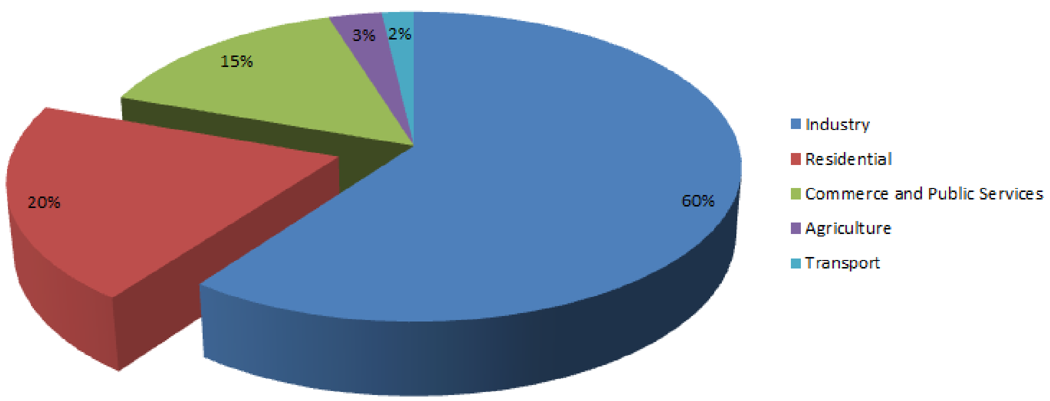
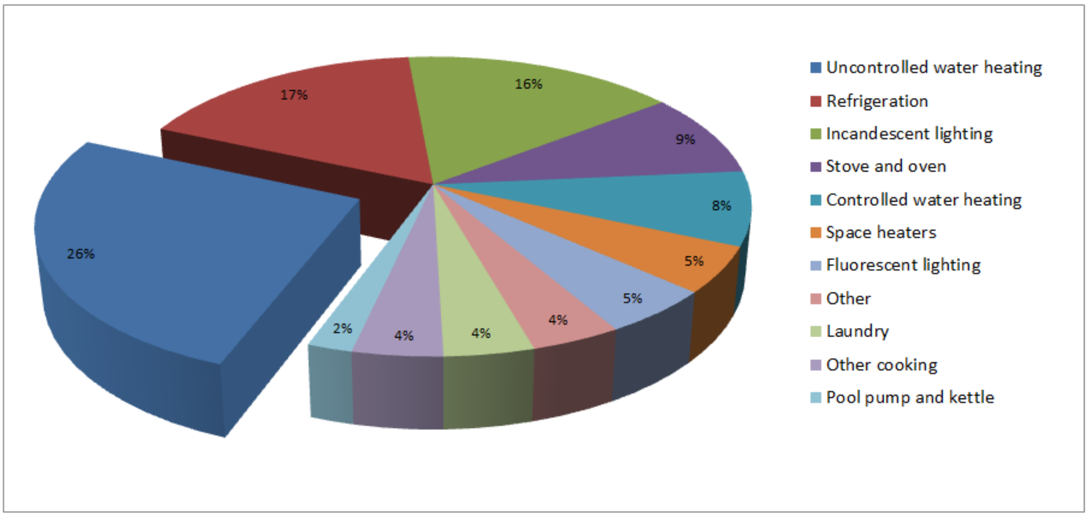


Figure 1.3: Breakdown of residential electricity consumption [10].



In South Africa water heating is typically achieved by means of an electric water heater (EWH) [11]. EWHs, often referred to as geysers, consist of a storage tank and an immersed resistive heating element [11]. They are frequently installed in the roof space of residential homes. The 5.4 million EWHs in South Africa contribute approximately 2,940 MW to peak load [12]. This is comparable to the output of a small power station or more than one stage of load shedding.

The proposed solution will take the form of a unit that can be retrofitted to an existing residential EWH installation. This unit will provide control and metering to the user. Another advantage of targeting this point of energy consumption is that EWHs have the ability to store energy in the form of heat. This can be leveraged to shift power use away from peak times as seen in Figure 1.4 to times of typically low consumption. According to Eskom EWHs are largely responsible for the peaks in electricity use between 07:00-10:00 and 17:00-21:00 [12]. Shifting this usage to times of decreased load would reduce the peak load that the power system would have to cater for.

1.4 Objectives

The end goal of this project was to create a unit to implement an intelligent EWH system. This system would have to meet the following objectives:

1. Reporting
   The system has to monitor the state of the EWH, include such values as temperature, water consumption, and power use, and report the data at an appropriate resolution to implement feedback based control. Additionally the data must be time-linked to facilitate load profiling and load profile shifting. The data should be simple to interpret and of sufficiently high resolution.

2. Control
   The system has to allow implementation of a chosen control scheme by means of actuators which control power supply to the EWH.

3. Remote
   The system must allow remote reporting and implementation of control as described previously.

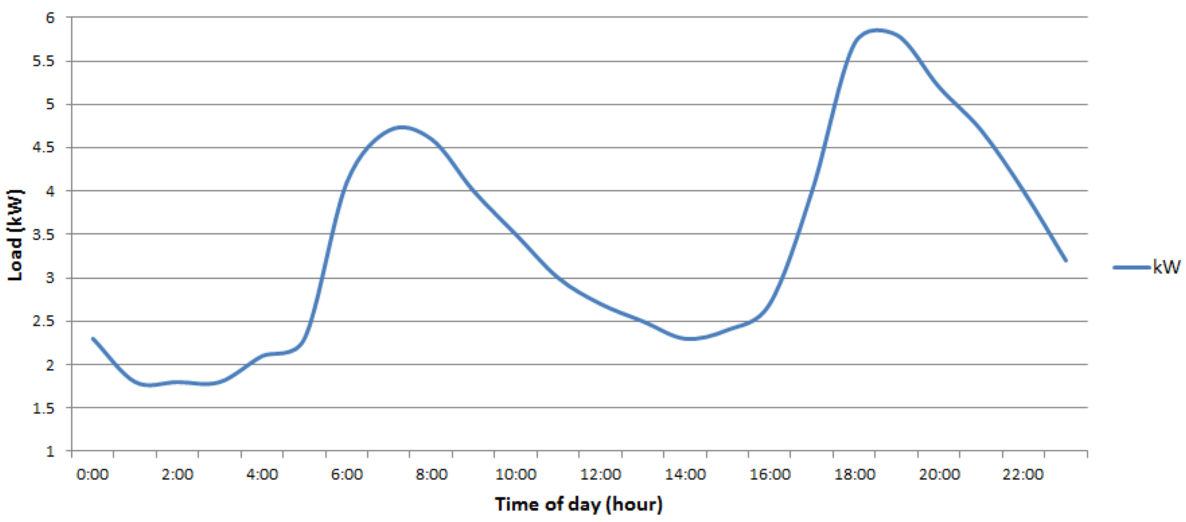
4. Risk mitigation
   The unit must be able to be retrofit to existing HWC installations without voiding the insurance. Since the HWCs to which the unit will be fitted will be of unknown structural integrity the unit must have means of detecting failure and mitigating damage and inconvenience in the event of such failure.

1.5 Scope

The system in question will be primarily focused on providing data for research purposes. The aim will be to produce a system that can be used to contribute to the body of knowledge regarding EWH operation and not to produce a commercial controller. Further, the focus of this research was on the development of an appropriate hardware solution. The details of the implementation of the database and website were carried out by a colleague.

The rest of this report will show the process that was followed in the creation of a unit that meets these objectives and the testing and implementation of the unit.

Figure 1.4: Typical residential load profile [10].



1.6 Layout of report

The contents of the remaining chapters of this report are described below.

Chapter 2 summarises the research that was done to provide a better picture of what will be required to achieve the objectives for the unit mentioned in Chapter 1. Previous implementations are studied to determine what the system will require to meet the stated objectives and what should be omitted or improved from existing systems. This research will be used to form the requirements on which the design decisions will be based.

In Chapter 3 the requirements for the system are formed based on the research done in Chapter 2. It then goes on to record the design process that was followed, the problems that were identified, and the iterations that the design went through to create the unit. Additionally, the decisions made during the design are justified.

Chapter 4 details the tests that the unit underwent, from a component level to the system as a whole, and records the results of those tests. It also describes the field trials that the unit underwent, and the results of the trials. Further, basic analysis of the data received from the units in the trial is done.

Finally, in Chapter 5, a conclusion is reached as to whether the unit met the stated objectives. A critical evaluation of how the unit met the various requirements is made and various problems encountered during the research are discussed and solutions are offered. Lastly, a recommendation is made as to the direction of further study based on conclusions that were drawn from the tests and data in Chapter 4.

Chapter 2

Literature Survey

2.1 Overview

To determine the requirements for the unit proposed in Chapter 1, similar projects and applications were analysed from existing sources. Conclusions were drawn from the analysis and from these conclusions requirements will be formed in the following chapter.

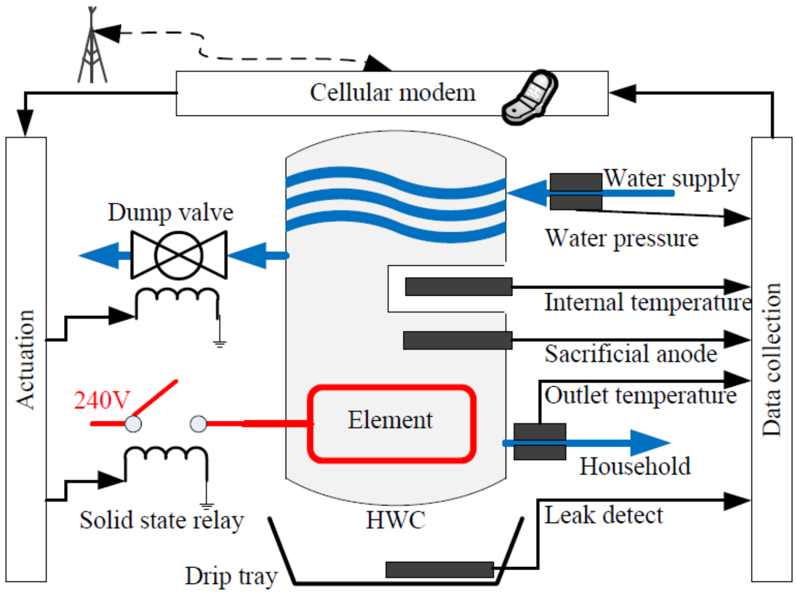
2.2 Proof of concept hardware solution

The authors of [13] describe a proof of concept system to remotely control and monitor EWHs in near real-time. The goal was to provide users with the ability to view consumption data and set temperature and schedules on an online platform. This was done to enable more efficient energy management on the part of the users and to enable power utilities to better understand the demand from the users. Additionally an attempt was made to mitigate the damage in the event of a structural failure of an EWH and to provide users with an indication of the structural integrity of their EWH. This with the aim of benefiting the insurance companies that frequently pay out in the event of an EWH failure [13].

2.2.1 Description of system

The system described by the authors of [13] can be looked at in three parts, sensing and actuation, theoretical analysis, and reporting. These will each be briefly described before being analysed. A diagram of the system is shown in figure 2.1.

Figure 2.1: EWH control and monitoring system implemented by Booysen et al.[13]



2.2.1.1 Sensing and Actuation

The temperature sensing portion of the system consists of two temperature sensors; one placed in a cavity between the outer shell and the inner tank of the EWH to monitor internal temperature, and one placed on the outlet pipe to detect events and to determine the ambient temperature in periods of inactivity [13].

A pressure transducer is placed on the inlet in order to detect any sudden pressure drops which may indicate a structural failure of the EWH. To further manage the risk, a sensor was placed in the drip tray of the EWH. This sensor would detect water in the drip tray and trigger in the event of a leak. Finally, the standard anode was replaced with a transducing anode which indicates the current anode depletion and therefore whether or not it is still protecting the EWH from corrosion. Power consumption was determined using a current transformer [13].

The use of the temperature sensor on the outlet pipe to determine ambient temperature could result in inaccurate readings, since the high thermal conductivity of copper would result in a reading higher than ambient even at rest unless it were placed far enough from the geyser to allow the heat from the last use to dissipate completely and sufficient time has elapsed for the pipe and the water in the pipe to cool completely. No mention of the required time is made in [13].

Using a temperature sensor to detect events in the manner suggested could result in sequential events being missed and would be unable to detect event duration with any accuracy. In [14] event detection was done using the same system used in [13] and it was found that if large usage events occur within seven minutes of each other the second event will be missed by thermal transient detector. Further, small usage events would not cause a sufficient rise in temperature at the sensor, and would not be detected. It is significant that [14] used an upstream water meter on a separate system to verify the accuracy of the detection algorithm. Additionally, thermal detection system was unable to detect the duration of a usage event to an accuracy of greater than two minutes [14]. This degree of inaccuracy would not be ideal for research purposes. Further, while the system is suitable for detecting events it is unable to determine water volume and flow rate.

The use of a pressure transducer in [13] to detect the future structural failure of a EWH due to overpressure is negated by the presence of the temperature and pressure release valve and the expansion relief valve that should have been installed with the EWH. The temperature and pressure valve is designed to vent in an over-temperature or overpressure situation to protect the EWH. The expansion valve is designed to allow for thermal expansion of the heated water. Further, any leaks would be detected by the drip sensor installed in the drip tray and would appear as usage events to the pressure transducer.

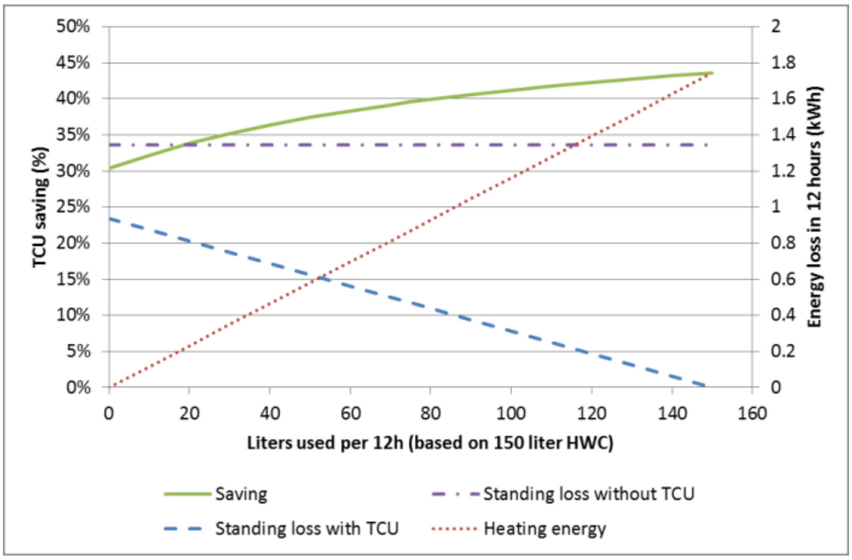
The inclusion of the integrated dump valve and drip sensor allows the home owner to respond timeously and remotely to the structural failure of a EWH. The dump valve can also be activated immediately by the on-board micro-controller when a leak is detected to minimise damage as far as possible. The use of a dump valve, however, will not completely prevent a compromised EWH from leaking and would still require a manual operation of the stopcock to shut off the water supply. Further, EWHs have built in drain valves that allow them to be emptied.

Using a solid state relay in conjunction with a temperature sensor in the cavity of the EWH to enable temperature and sensor control is an efficient, cost effective and safe way of implementing external temperature control. The temperature sensor in the cavity of the EWH was used to monitor the internal temperature and used as an input to the micro-controller for software set point control using the solid state relay. The relay was used to control power to the heating element before thermostat. Therefore it does not replace or override the mechanical thermostat. This means that in the event of the micro-controller, relay or temperature sensor malfunctioning the internal temperature will be limited by thermostat. Further, it does not compromise the integrity of the EWH or require a custom thermostat to be designed or fitted.

2.2.1.2 Theoretical analysis

In [13] Booysen et al. undertook a detailed heat dissipation analysis in which the benefit of implementing schedule control was proven mathematically. The full analysis can be found in [13]. Using the parameters shown in 2.1 an energy reduction of 14.7% was calcu-

Figure 2.2: TCU Energy saving for different consumption levels[13]



lated for heating schedule designed to only heat the water right before it was used. The analysis was repeated for a reduction of 15°C in thermostat setting on the EWH. This alone resulted in a saving of 16.6% [13].

This energy saving is due to the manner in which the internal temperature of a EWH decays. The following equation models the temperature loss in an EWH[13]

$$T_{internal}(t) = T_{ambient} + (T_{internal}(0) - T_{ambient})\, e^{\frac{-t}{cmR}} \tag{2.1}$$

The time in days is shown as t, c is the specific heat capacity of water, m is the mass of the water in the EWH and R is thermal resistance of the EWH [13]. It can be seen from the equation that the internal temperature of an EWH decays exponentially. To continually maintain the desired internal temperature of an EWH keeps the temperature at the point of maximum standing loss. The rate at which an EWH cools decreases as it approaches the ambient temperature.

Booysen et al. also determined that the equivalent savings achieved by implementing schedule control are heavily dependent on the amount of water used every heating period [13]. This is shown most clearly in figure 2.2. As the amount of hot water used every 12

EWH Capacity	150 liter
Volume of hot water used per cycle	75 liters
Cycle period	12 hours
Standing loss (manufacturer specification)	2.59 kWh/day
Thermostat set temperature	60°C
Ambient temperature	20°C
Cold water temperature	20°C

Table 2.1: Parameters used for the heat dissipation analysis [13]

hours approaches the capacity of the EWH the savings are maximised. This is significant in that the heaviest users have the most to gain from the implementation of schedule control.

In a study conducted to determine hot water usage habits of South African residents Meyer identified the demographic with the highest average consumption. This demographic consumed approximately 91.4 liters of hot water per person each day. The average occupancy of a residence in this demographic is given as 3.1 [11]. Therefore it can be safely assumed that there are households that consume in excess of 140 litres of hot water in a 12 hour period. According to figure 2.2 these households would have equivalent savings in the region of 40%.

The strong mathematical case made by Booysen et al. for the implementation of schedule control is confirmed by the results obtained from the field study. When a timer was used to implement a schedule where the water was heated only immediately before it was used an energy saving of 16.3% was the result. This value closely matches theoretical calculation. The discrepancy is likely due to the assumptions made for daily hot water consumption, ambient temperature and inlet water temperature. A further experiment in which thermostat was decreased by by 15°C resulted in a saving of 16.6%, exactly as predicted in the theoretical calculation[13].

Figure 2.3: SMART Platform user controls[13]

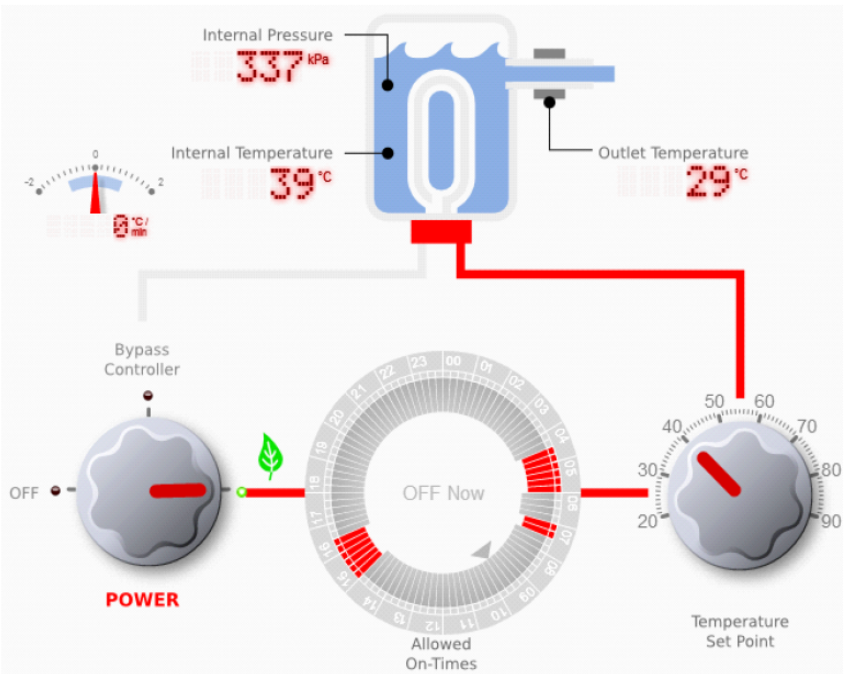
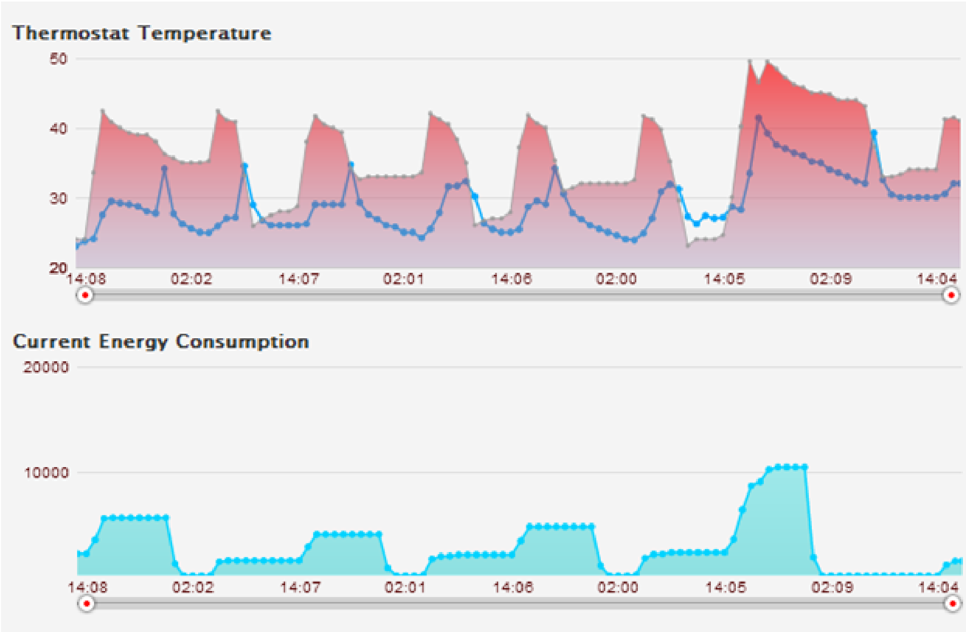


Figure 2.4: SMART platform user feedback[13]



2.2.1.3 Reporting

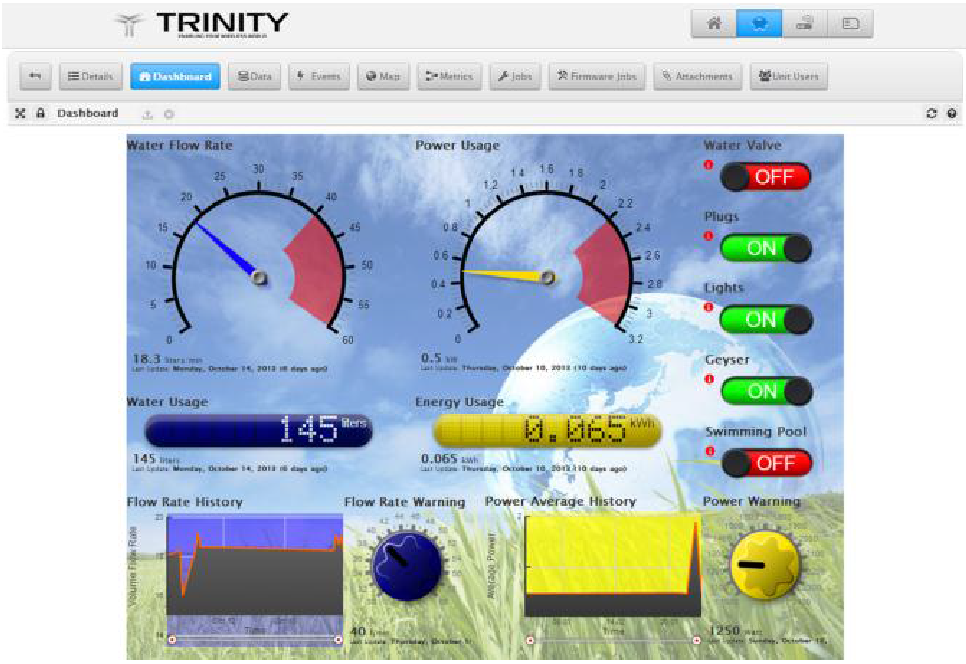
In the system employed by Booyen et al. reporting and control were implemented by means of a General Packet Radio Service (GPRS) cellular connections. These connected to Trinity's SMART platform by using an Access Point Name (APN). The cellular connection was achieved by means of a modem installed with the unit. The system was configured to send status updates to the database once every minute [13].

The SMART platform provides a machine to machine (M2M) communications platform with a built-in database, internet portal, and visual data models and configurable controls [13]. These interfaces were used to provide the users highly visual control and feedback as shown in figures 2.3 and 2.4. This feedback was the cause of one of the most notable results of the study. When users were provided with feedback on their usage patterns and power consumption they were observed to alter their behaviour which resulted in much higher savings than could otherwise be achieved. In one instance an energy saving of 25% was experienced [13]. It is clear that the provision of timely, visual feedback is also important in the effort to reduce power consumption.

2.3 Household water and electricity monitor and control

In [15] Müller et al. presents a general solution for a household utility monitor. This system was used to provide smart metering for both water and electricity. The aim was to provide timely feedback of consumption data to the user. Currently this information is

Figure 2.5: SMART metering dashboard[15]



typically available to the user only as part of the monthly billing process. This is not effective in raising awareness of consumption due to that fact that the user most frequently billed weeks after the event[15]. The utilities that were measured, water and electricity, will be looked at in turn in order to evaluate the methods measurement methods used.

Müller et al. also made use of Trinity's SMART platform for remote data visualization and control [15]. A screenshot of the webpage providing the user with access to the data and control of the monitor can be seen in figure 2.5. A disadvantage associated with the SMART platform is that it is not designed to provide access to the database from outside the platform. This inhibits dissemination of the data which can make make advanced data analysis more challenging.

2.3.1 Water measurement

In order to measure the water flow Müller et al. made use of an orifice flow meter of his own design citing the expense and complexity of existing electronic meters. Orifice flow meters use the pressure differential caused by an obstruction in a pipe to determine water flow rate by applying Bernoulli's equation [15]. Flow rate measurements can then be integrated over time to determine water volume.

In practise, the pressure differential required for an orifice flow meter to operate results in an loss of pressure after the meter. This is not ideal from the point of view of any occupants of the household. Measurement of water consumption would be better achieved by means of a simple electro-mechanical meter with an output indicative of volume. Muller et al. noted that the orifice flow meter was accurate to within 1% for flow rates beween

$4l/min$ and $70l/min$ [15]. However, any measurement error will be integrated over time resulting in an incorrect result for volume. Transient pressures created by opening and closing taps and thermal expansion of the water have the potential to further introduce error into the measurement.

2.3.2 Power measurement

Müller et al. implemented power measurement using a power measurement integrated circuit (PMIC) [15]. This is a purpose designed IC used to accurately determine voltage, current power and power factor. It has the advantage of using both a reference current and a reference voltage for greater accuracy.

A disadvantage of this system as given by Müller et al. is the lack of electrical isolation between mains and the measurement circuit [15]. This would pose additional risk to to any operators and the measurement unit itself.

2.4 Smart geyser with Wi-Fi access

In the implementation of a smart geyser (EWH) system Brown, et al. explored the possibilities presented by providing access to feedback and control by means of a self-hosted Wi-Fi access point. Users within range of the system could connect to the system through the accesss point by means of smart-phones, tablets or laptops. An intuitive website was hosted on the device to provide control and feedback. The system was designed to measure temperature at three points, power and energy consumption and hot water consumption [16].

2.4.1 Website

One of the goals of the project was to evaluate the use of Wi-Fi and a website to provide feedback and control. The unit provided a completely self contained solution because the connection point was generated by the device and the website was hosted on the on-board micro-computer [16]. This allows greatly improved flexibility as far as data manipulation and display are concerned. A screen-shot of the page of the website can be seen in figure 2.6.

A disadvantage of this implementation is that the user does not have access to their EWH from outside the home and the neither data nor control would be available to power utilities for load planning or demand management. Another disadvantage is that the processing power required to host a website and access point require expensive hardware [16].

2.4.2 Measurement and actuation

As in the study done by Müller et al. a PMIC was used to determine the power. Voltage and current transformers were used to electrically isolate the unit from the 220V mains supply. A commercial volumetric flow meter was used to determine water consumption. The unit was fitted with a reed switch which emitted a pulse every half litre. These pulses were counted by the hardware to determine both flow rate and water use [16].

The element was controlled in the same manner as employed by Booysen et al. but the response to the detection of a structural failure of the EWH was by means of a shut-off valve which would stop supply of water to the EWH when activated. This would limit damage in the event of a EWH failure to what could be caused by the contents of the EWH itself [16]. This system made use of a solenoid valve to cut off the water supply. Two disadvantages were found with this system. The first was that the solenoid consumed a great deal of power and the second was that the solenoid has to be energized constantly for the duration of the shut-off period. This meant that the power consumption was raised for extended periods of time and the solenoid was liable to overheat.

Many of the subsystems implemented by Brown et al. have already been discussed in this study. What is notable is that Brown et al. tested the accuracy of the measurements from each of the sensors. The power was seen to be within 3% accuracy. What is interesting is that the sensors were all accurate to within 9% despite being taped to the exterior

Figure 2.6: ECO Geyser webpage[16]

of the pipes at the inlet and outlet and fixed to the faceplate of the EWH [16]. Table 2.2 shows the accuracies of each specific sensor. Further, the sensors displayed a response of 0.6 °C a second when a rapid temperature change was effected on the pipes. [17]. This is more than than adequate for an update time of one minute.

2.5 Data analytics and advanced reporting

Using data from the system employed in [13], augmented with local weather data and water consumption measurement, Nel et al. implemented several systems in which advanced reporting and analysis techniques were used to provide users with information in an ideal form to implement power savings [14][18].

2.5.1 Event detection

In [14] Nel et al. used a temperature sensor attached to the outlet of an EWH to detect and classify usage events on a day to day basis. The usage events are detected by applying an algorithm to the transient temperatures detected by the outlet temperature sensor. The usage events are used to determine an optimal control schedule for the EWH in terms of both energy consumed and hot water availability. Further, a mathematical model of the EWH was used to predict the future effects of user-chosen control schemes. This data and the various control options were made available to the users by means of a smart-phone application [14].

A screen-shot of the smart-phone application can be seen in figure 2.7. Using only the temperature sensor, the algorithm is able to detect usage events with an accuracy of 91%. Event duration is accurate to within 2 minutes 79% of the time [14].

It must be noted that while the algorithm detects events and event duration, it is unable to determine either flow rate or water volume. A water meter would still be required if these values are to be determined with any accuracy. Accurate water consumption data will be needed to accurately estimate the energy consumption.

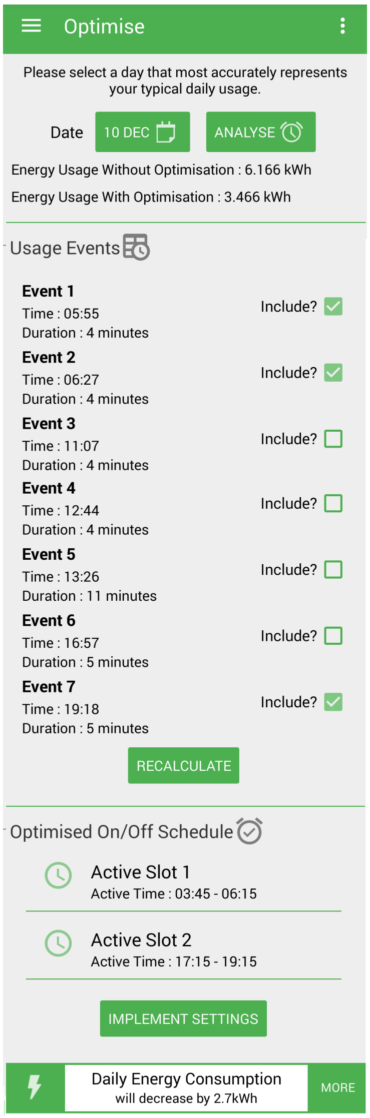
2.5.2 EWH simulation model

In [18] Nel et al. developed a mathematical model of EWHs that can be used to accurately and rapidly simulate EWH operation. The model used for the simulation is simple and efficient enough for use on mobile devices or for big data processing. The details of the model can be found in [18]. The model was able to estimate energy consumption to within 5% for thermostat control and 2% for schedule control [18]. A graph showing the measured energy input against the calculated energy input can be seen in figure 2.8.

Position	Sensor temperature	Measured temperature	Error	% Error
Inlet	20°C	20.7°C	0.7°C	3.38
Internal	67°C	73.4°C	6.4°C	8.72
Thermostat setting	70°C	73.4°C	3.4°C	4.63

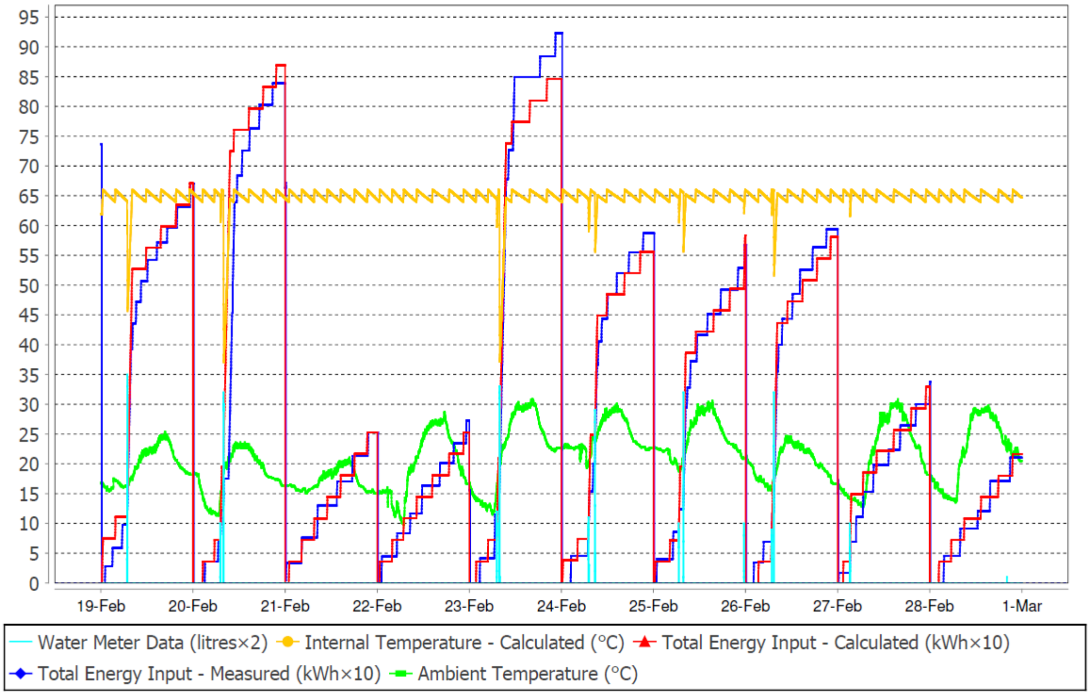
Table 2.2: Results for temperature measurement tests [17]

Figure 2.7: Optimise page of smartphone application[14]



A number of separate information sources were required to provide the required data to implement the model. Local weather data was obtained from weather monitoring stations and scaled to give the ambient temperature used in the calculation [18]. This is highly prone to error, weather station data may be unavailable for the location in which the EWH is situated and variations in the EWH location would vary the value by which the ambient temperature needs to be scaled. Further, users may be reluctant to share the location of their homes simply for the purpose of an already estimated temperature reading. The obvious solution is to measure the ambient temperature in proximity to the EWH directly. Again, inlet temperature was estimated based on standard ground tem-

Figure 2.8: Graphed output of EWH model[18]



perature temperatures based on the seasons [18]. This discounts the possible preheating of the inlet water to the ambient temperature while in the pipe.

In [18] Nel et al. describes the sensitivity of the energy estimation to errors in the input values. The model is most sensitive to an error is set temperature, where a 5 °C error can cause the estimation error to increase by 8%. However, a 10% error in the value for the inlet temperature will result in an additional estimation error of 2% to 4%. Nel then goes on to state that these errors would prove to be a problem when estimating the energy used by a large number of EWHs [18]. Finally, the data would need to be available in real time in order to provide accurate daily energy consumption data.

All these factors indicate that for a simulation model of an EWH, such as the one implemented by Nel et al. in [18], to be most effective, ambient temperature and water inlet temperature should be measured directly by sensors and the values reported by the monitoring unit. A trade-off could be made between additional thermal measurements that would allow the simulation model to be used for accurate power estimation or measuring the power consumption directly.

2.6 Water consumption study

In [11] Meyer conducted a study in which the hot water consumptions of 770 homes was measured directly over the course of a year. Daily measurements were taken in 331 homes while usage of the remaining homes was taken every month [11]. Meyer was careful to include a full spectrum of dwelling types and demographics in the study. Volumetric flow meters were installed in the houses and the readings were manually recorded once a month. In the case of the hourly recorded values digital flow meters were used in conjunction with a 60 minute interval recorder [11].

Meyer noted that two distinct peaks in water consumption occurred each day. One in the evening and one in the morning. This can be seen in the average hourly consumption for low, medium and high density houses shown in figure 2.9. Furthermore the average daily water consumption has a strong positive correlation of 0.95 when compared with the residential load profile as shown in figure 2.10.

From this it can be safely hypothesized that the increased use of hot water at the peak times observed in the load profile contribute to the increased electricity use.

Manually recording the data has the distinct disadvantage of requiring the presence of a person at the house in order to grant access to the person tasked with checking that day's data. Meyer noted that in several instances problems with gaining access caused the meter reader to make an appointment for a different day and the data had to be adjusted to allow for the additional passage of time. Remote digital metering would avoid this problem altogether, provide higher resolution, real time data, and allow the data to be entered into a database automatically.

2.7 Findings

From the study by Booysen et al. it can be seen that there is a definite value from a power saving point of view in creating a system that would be able to employ both timer

Figure 2.9: Average daily water consumption[11]

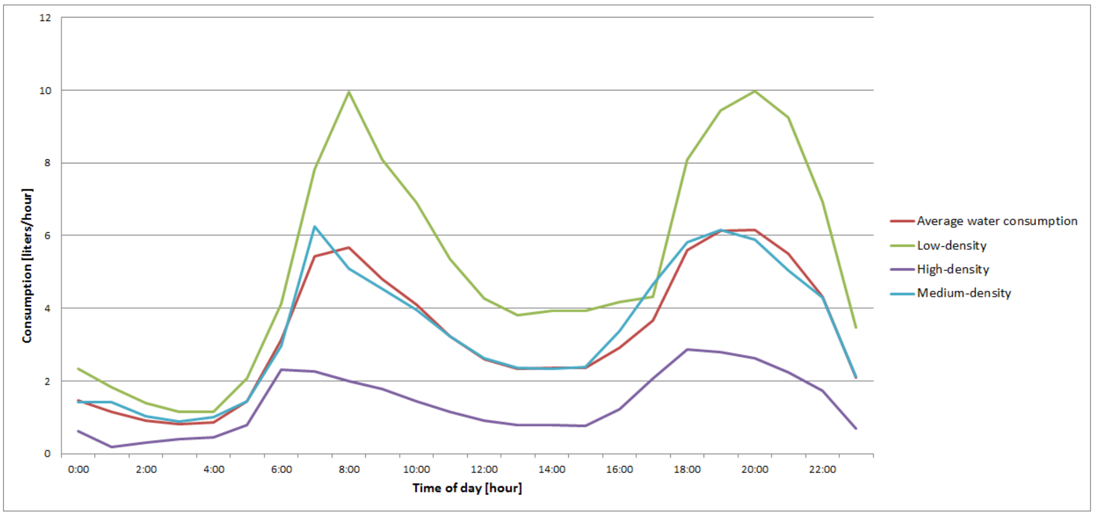
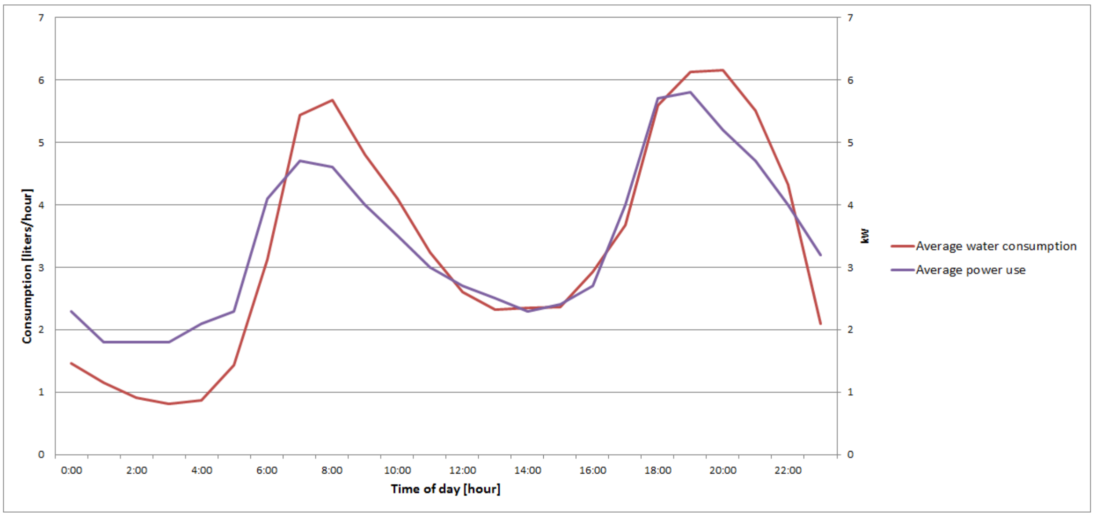


Figure 2.10: Average daily water consumption and load profile[11]



and temperature control. This by means of direct control of power to the element and inclusion of non-invasive internal temperature sensors. From Meyer it can be seen that such a system has the potential to reduce peak energy usage since water usage peaks at the same time as residential power usage.

The benefit of timely, visual feedback is seen from the studies by Booysen et al. Reporting the data to the user in such a way as to encourage better usage behaviour is as important as the implementation of control. Further, from the study by Müller it can be can be seen that the data be should be readily available for analysis.

Various means of detecting structural failure of an EWH and then responding timeously to reduce the damage were found in the systems employed by Booysen et al. and Brown. The simplest method of detecting a leak appears to be a drip sensor mounted in the drip tray of the EWH. The most effective damage mitigation method would be an electrically activated valve to shut off the water supply in the event of a leak and a relay to shut off power supply to the device. If activated, the user would be informed and the element would not receive power.

The most accurate and safest method of measuring the power consumption of the EWH is the use of isolated voltage and current references in conjunction with a dedicated PMIC as seen in the studies by Brown and Müller.

From the research done by Nel the need for accurate recording of inlet, outlet, internal, and ambient temperature and water consumption and are seen. This data would be needed in order to implement the simulation model for an EWH and further refine the event detection algorithm.

Finally, none of the studies shown had data on the effect of hot water temperature on total hot water use in usage events. For this reason it would be valuable to gather data on both hot water and cold water consumption in order to determine the effect of changing hot water temperature on the percentage of hot water used each usage event.

Chapter 3

Design

3.1 Overview

In this chapter the requirements for the proposed system will be determined based on the research done in Chapter 2 and the objectives in Chapter 1. The subsystems will be designed in order to fulfil these requirements. Flaws in the design that were revealed in testing will be briefly described and the subsystem redesigned to eliminate it.

The hardware design went through three iterations, namely MkI, MkII and MkIII, and the software went through two. MkI was the completed on vero-board and was used to evaluate the operation of the various subsystems as a single unit. A PCB was laid out for MkII and MkIII both of which incorporated the changes made as a result of the evaluation of the previous versions.

3.2 Requirements

The requirements for the system were formed in order to fulfil the objectives given in Chapter 1. The decisions were informed by the research done in Chapter 2.

3.2.1 Functional requirements

ID	Requirement
1	**Reporting**
1.1	The system shall measure ambient temperature.
1.2	The system shall measure inlet temperature.
1.3	The system shall measure outlet temperature.
1.4	The system shall measure internal temperature.
1.5	The system shall measure hot water consumption.
1.6	The system shall measure cold water consumption.
1.7	The system shall measure measure power use.
1.8	Measurements shall be made available to the user.
1.9	Measurement data shall be stored.
1.10	Data integrity shall be maintained
1.11	The user shall receive near real-time feedback
2	**Control**
2.1	The system shall control operation of the element of the EWH.
2.2	The system shall control water supply to the EWH.
2.3	The system shall implement operation commands.
2.4	The system shall prevent execution of unsafe operation commands.
2.5	The user shall have near real-time control
3	**Remote**
3.1	The system shall update measurements to central server and database.
3.2	The system shall receive remote operation commands.
3.3	The system shall default to a safe state that is convenient to the user if communication fails.
4	**Risk mitigation**
4.1	The system shall detect structural failure of EWH.
4.2	The system shall minimize damage when a leak is detected.
4.3	The system shall have precautionary control of water supply to the EWH.
4.4	The system shall have precautionary control of power supply to the EWH.
4.5	The system shall report to the server when a leak is detected.

3.2.2 Non-functional requirements

Reporting		
ID	**Requirement**	**Derived from**
RP[1]	All temperatures shall be measured to within 10% accuracy	1.1 1.2 1.3 1.4
RP[5]	Temperature sensors must be able to accurately measure temperatures from 0°C to 100 °C	1.10
RP[6]	Hot water flow rate shall be determined on the system once a minute.	1.5
RP[7]	Daily cumulative hot water usage shall be determined on the system.	1.5
RP[7]	Daily cumulative hot water usage shall be accurate to within 10%.	1.5
RP[6]	Cold water flow rate should be determined on the system once a minute.	1.6
RP[7]	Daily cumulative cold water usage should be determined on the system.	1.6
RP[7]	Daily cumulative cold water usage should be accurate to within 10%.	1.6
RP[10]	Power consumption shall be measured to within 10% accuracy.	1.7
RP[10]	Power consumption of 0W to 4kW shall be measured.	1.7
RP[10]	Electrical isolation shall be maintained in the power measurement.	1.7
RP[12]	Cumulative daily energy use shall be integrated from power.	1.7
RP[12]	The time step for the energy integration shall be less than one minute.	1.7
RP[13]	Current power consumption shall be reported by the system once a minute.	1.7
RP[14]	Consumption data shall be made made available to the server in human-readable format	1.8
RP[15]	The system shall include feedback indicating if the switching mechanism for the element is open or closed.	1.8
RP[16]	The system shall report the presence of water in the drip tray.	4.5
RP[17]	Cumulative daily totals shall be reset automatically at 00:00:00 GMT.	1.8
RP[18]	System shall report data using UDP .	3.1
RP[18]	System shall report data using to a predetermined IP address .	3.1
RP[19]	The system shall use less than 1MB of data daily.	3.1
RP[20]	Data shall be reported in a set with all measured parameters.	1.8
RP[22]	The system shall maintain its own time-stamp with a drift of less than 5 seconds per day.	1.10
RP[23]	The system shall send its time-stamp with each outgoing data transmission.	1.10

Control		
ID	**Requirement**	**Derived from**
C[1]	The system shall be able to receive commands for the element control.	2.1
C[2]	The system shall be able to receive commands for the water flow control.	2.2
C[4]	The system shall prevent power being supplied to the element while water supply is cut off.	2.4
C[5]	The system shall control power supply to the element using an energy efficient relay	2.1
C[5]	The system shall control power water supply using an energy efficient valve	2.2.
C[6]	The system shall receive commands to synchronize time to an external reference	1.10.

Remote		
ID	**Requirement**	**Derived from**
R[1]	The system shall report data every minute.	1.11
R[2]	System shall include provision for receipt of commands via UDP.	3.2
R[3]	The system shall be able to implement temperature control from commands sent by an external server.	2.3
R[4]	The system shall respond to remote commands within 2 minutes.	2.5
R[5]	System shall default to a safe mode if communications with the server is lost for ten minutes.	3.3

Risk Mitigation		
ID	**Requirement**	**Derived from**
RM[1]	Shall be able to detect presence of water in the drip tray of the EWH.	4.1
RM[1]	The system shall check for water in the drip tray after a power cycle.	4.1
RM[2]	The drip tray shall be checked for water every 100ms.	4.1
RM[3]	The system shall respond within two seconds to the detection of water in the drip tray.	4.2
RM[4]	The system shall detect a drip if water is present in the drip tray for more than four seconds.	4.1
RM[5]	The output of the drip sensors shall be detectable for tap water with an atypically low conductivity of 1mS/m.	4.1
RM[5]	The output of the drip sensors shall be detectable for water between 0°C and 100°C	4.1
RM[]	Shall automatically go into "Burst protection" state when a leak is detected	2.3
RM[7]	Water supply shall be automatically cut on entering "Burst protection" state.	4.2
RM[8]	Power to the element shall be automatically cut on entering "Burst protection" state.	4.2
RM[6]	While in "Burst protection" power activation commands will be ignored.	2.3
RM[6]	While in "Burst protection" water supply activation commands will be ignored.	2.3
RM[6]	The "Burst protection" can only be cleared by a command from the user or a power cycle	2.3
RM[9]	Shall include water detection sensor reading with every data update.	1.8
RM[10]	All sensors must be protected from excess current draw caused by short circuit.	4.2
RM[11]	All inputs to the processor must be protected from short circuits on the sensors.	4.2

The design process that was followed in order to implement these requirements will be shown in the following sections. The tests in which adherence to the requirements was determined are detailed in Chapter 4.

3.3 Hardware Design

The hardware can be divided into five subsystems; power supply, processing, sensors, actuation, and communication. The design for each of these subsystems will be shown in the following sections. A simple functional diagram is shown in Figure 3.1.The hardware design went through three iterations as the various subsystems were tested. These iterations were designated as MkI, MkII and MkIII of the EWH controller.

MkI, shown in Figure 3.2 was constructed on vero-board for the sake of expediency and was used to evaluate the operation of the subsystems. MkII and MkIII, Figures 3.3 and 3.4 respectively, were developed with field trials in mind. The circuit boards were manu-

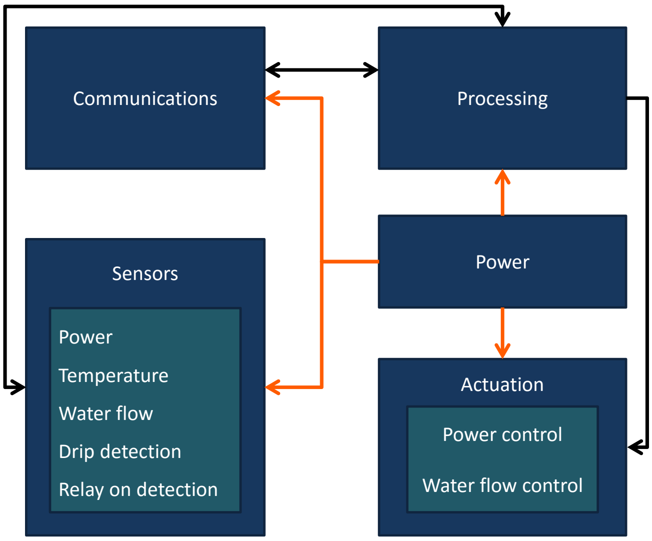


Figure 3.1: Functional diagram of EWH controller

factured commercially and populated in-house. At the time of writing the MkIII boards were being manufactured.

3.3.1 Power supply

All of the power supplies for the controllers were designed to supply the controller with the required voltages while being fed off the same supply that feeds the EWH. In essence, the power supply would need to take a supply of 220V AC and convert it to the voltages required by all the subsystems.

Design for MkI and MkII

Three different supply voltages were required by the subsystems on MkI and MkII. The sensors and the micro-controller chosen for MkI and MkII required a 5V supply. The power measurement IC required 3.3V. The modem required a 5V - 32V supply capable of

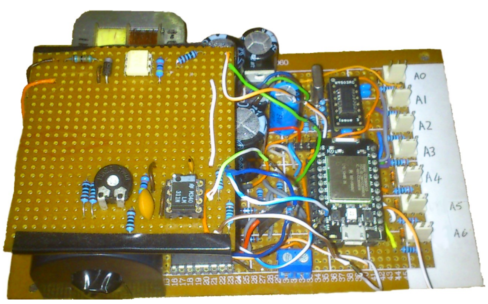


Figure 3.2: EWH Controller MkI

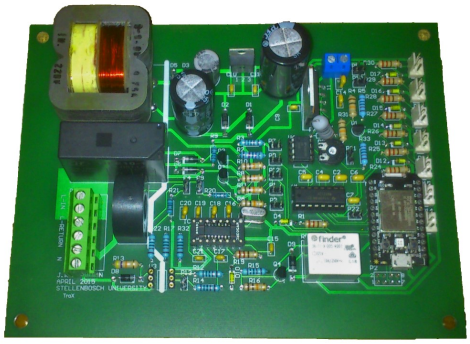


Figure 3.3: EWH Controller MkII. External modem not shown.

sourcing 650mA and the actuators both required 12V. Further, an AC voltage reference was needed to accurately determine the power.

To efficiently supply all these systems a centre tapped 6-0-6 transformer was used. A secondary was used as the voltage reference for the power measurement. The other secondary was used to supply a voltage doubler circuit that used to charge a 4700μF capacitor up to the 18V that was used to activate the latching valve and the relay. These actuators are discussed in detail in the actuation section. Each secondary was then half wave rectified to provide an unregulated 8V supply that was used to supply the modem and the 5V linear regulator. The 3.3V needed for the power measurement IC was supplied by the 3.3V regulator on the micro-controller board. The circuit used to supply these voltages can be seen in Figure 3.5.

This layout was chosen to provide a common ground between the ac voltage reference and the power measurement IC. The AC voltage doubler could not be on the same secondary as the voltage reference because the AC wave would be distorted by the charging of the capacitors. Finally, this arrangement permitted the linear regulator to regulate down from 8V instead of 12V. This limited power dissipation in the form of heat produced by the linear regulator.

Figure 3.4: EWH Controller MkIII with on-board modem

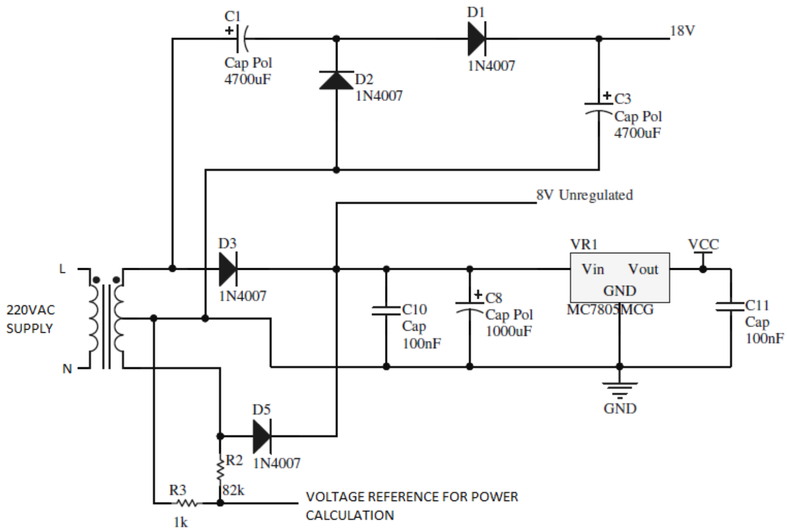


Figure 3.5: MkI and MkII power supply circuit

Table 3.1 shows the power requirements for several of the subsystems. It can be seen that by far the greatest consumers of power are the actuators. Fortunately, as will be detailed in the actuation section, both the relay and the valve are latching and consume the given power value intermittently and for only 100ms at a time. This allowed the transformer to be chosen based almost entirely on the requirements of the modem and the processor. A 9VA transformer was chosen to provide power for the 6.7W modem and processing load and to have ample margin for charging the capacitors and to supply the minimal power required by the sensors.

Design for MkIII

For the MkIII the design was optimized by removing the 5V rail, determining the power without a voltage reference and using switching regulators to step down the rectified voltage. For these reasons a transformer with a single secondary could be used. The output was full bridge rectified and smoothed with a 4700μF capacitor. Two separate switching regulators then regulated the 12V supply down to 3.3V for the processor and sensors and 3.7V for the u-blox modem that was used for MkIII. Power requirements for the MkIII are greatly reduced due to the used of a u-blox GSM module instead of a modem and the use of a bare processor instead of a micro-controller with integrated

Component	Operating voltage	Peak current	Peak power
Processor	5V	0.3A	1.5W
GSM Modem	8V	0.65A	5.2W
Latching relay	12V	0.25	3 W
Latching valve	12V	2.7	32.4W

Table 3.1: MkII Subsystems with power requirements

Wi-Fi. Despite this, a 10VA transformer was still used to allow the inclusion of add-on boards providing greater functionality.

3.3.2 Processing

The EWH controller required a processor to process the data from the sensors before it was transmitted to the central server via the modem. Further, the processor was required to implement control commands that were received from the server using the actuators. Finally, the processor was needed to implement fail safe control measures if communication with the server was lost.

Design for MkI and MkII

The Particle Core development kit, hereafter referred to as the Core, was chosen for use with the MkI and MkII EWH control board. This was because the Core features an integrated Wi-Fi module and cloud support including over-the-air firmware updates [19]. It was found to be the most cost effective solution to evaluate the use of Wi-Fi as a communication medium.

The Core features an ARM 32-bit Cortex M3 processor that operates at 72MHz. The processor possesses 128kb of flash memory and comes from the factory with a boot-loader enabling over-the-air firmware updates pre-installed. Wi-Fi communication is included in the form of an embedded CC3000 module by Texas Instruments [19]. All told, there are 18 I/O pins available on the Core. The pin assignments are listed below.

- 2: Serial modem communication.
- 2: Serial Power measurement IC communication.
- 4: Analogue temperature measurement.
- 1: Analogue leak detection.

Figure 3.6: Particle Core micro-controller

- 2: Hot and cold flow meter measurement.
- 1: Modem relay switching.
- 2: Latching relay switching.
- 2: Latching relay switching.
- 1: Monitoring of latching valve.
- 1: Monitoring of latching relay.

As can be seen above, all 18 of the I/O pins available on the Core were used.

Problems with design for MkI and MkII

Testing found several problems with the Core. Early testing proved Wi-Fi to be an unworkable solution for devices that are implemented in the roof space. The Wi-Fi connection on the Core proved to be too sensitive to signal quality and distance from the transmitter. Further, over-the-air firmware updates failed intermittently and occasionally required the device to be physically reset before the firmware already loaded on the device would resume operation. For this reason alone, given the inaccessibility of the devices, over-the-air firmware updates using the factory loaded firmware was not considered. Further, the background management of the CC3000 caused the firmware to undergo intermittent delays. When the EWH control firmware was updated to address these issues the Wi-Fi was disabled entirely and the devices were programmed over USB.

Re-design for MkIII

With Wi-Fi disabled, the high cost and complexity of the Core were no longer justified. MkIII was designed to make use of an ATXMEGA128A4U by Atmel. The XMEGA was chosen because of the readily available support, documentation and supporting programmers.

3.3.3 Sensors

This subsystem can be broken down still further into input protection, temperature measurement, power measurement, water consumption measurement, leak detection and relay activation detection.

3.3.3.1 Input protection

The temperature sensors, water flow meters and drip detection sensors would be deployed in an uncontrolled environment so it was deemed necessary to protect the inputs of the

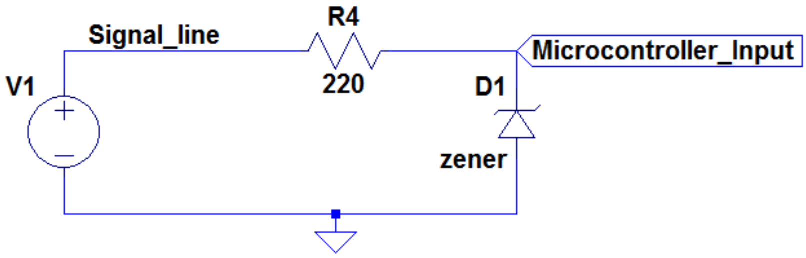


Figure 3.7: Protection circuit

micro-controller from a sensor were the 5V supply had shorted to the signal wire. This would be as a result of either moisture or compression compromising the insulation.

Design for MkI and MkII

A passive protection circuit was designed around 3.3V zener diodes. If the sensor voltage rose higher than that the breakdown voltage of the zener diode it would breakdown, passing current to ground causing a voltage drop across the resistor and input to the processor would be limited to 3.3V. The maximum voltage that could be reasonably expected to contact the sensor line is the 5V supply off which the sensors are driven. The resistor

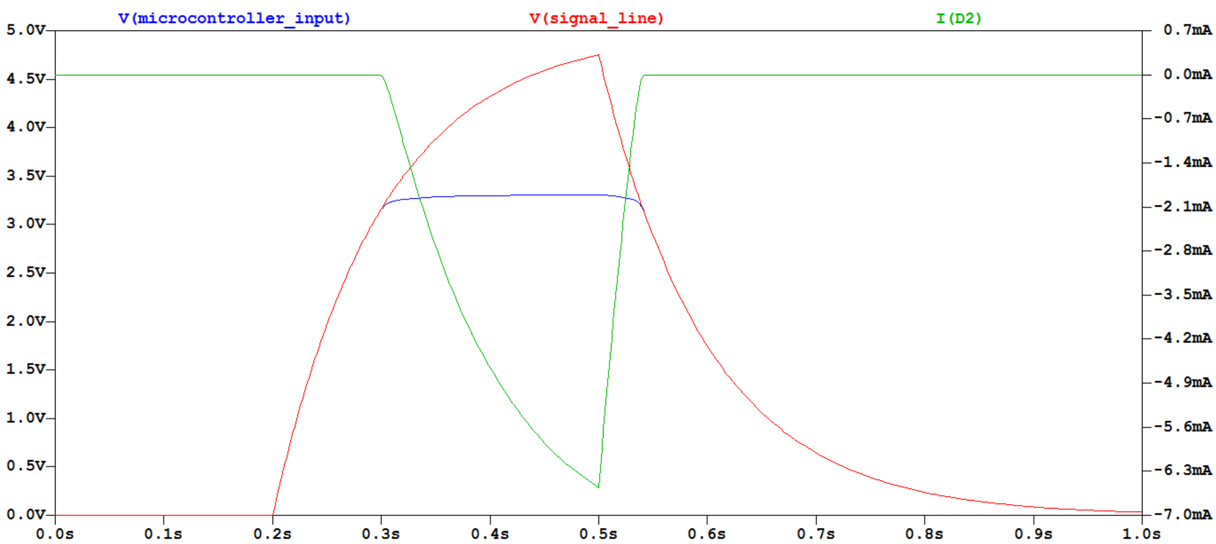


Figure 3.8: Simulation results

was chosen to limit the current through the zener diode as follows.

$$P = V \times I \tag{3.1}$$

$$I_{zener} = \frac{V_{supply} - BV_{zener}}{R} \tag{3.2}$$

$$\therefore P_{zener} = \frac{V_{supply} - BV_{zener}}{R} \times BV_{zener} \tag{3.3}$$

$$\therefore R > \frac{V_{supply} - BV_{zener}}{P_{zener}} \times BV_{zener} \tag{3.4}$$

Where I_{zener} is the current through the zener diode, P_{zener} is the power rating of the zener diode, V_{supply} is the supply voltage and BV_{zener} is the breakdown voltage of the zener diode. If V_{supply} is to be 5V and the power rating of the zener diode is 0.5W, then the equations yield the following results.

$$R > \frac{5 - 3.3}{0.5} \times 3.3 \tag{3.5}$$

$$R > 11.22\Omega \tag{3.6}$$

$$R \text{ chosen as } 220\Omega \tag{3.7}$$

$$\therefore I_{zener} = \frac{5 - 3.3}{220} \tag{3.8}$$

$$I_{zener} = 7.73mA \tag{3.9}$$

The circuit was implemented on all of the sensor input lines, the temperature sensors, water flow sensors and the drip sensor for the first and second iterations of the design, MkI and MkII.

Simulation

The operation of the protection circuit, shown in Figure 3.7, was verified by a simulation in LTSpice and the results are shown in Figure 3.8. As can be seen in figure 3.8 the maximum current through the zener diode is approximately 6.5mA. This is consistent with the value that was calculated.

Problems

No problems were experienced with the protection circuit. To the contrary, the author experienced two instances where a short occurred between the sensor line and the 5V supply during field tests. The inclusion of the input limiting circuit prevented damage to the input of the micro-controller.

Re-design for MkIII

In the third iteration of the design, MkIII, the 5V rail was done away with to reduce complexity. This negated the need for the protection circuit so it was not included. Only the 220Ω series resistors were retained to prevent the input pins of the processor from sinking too much current at start-up when the internal resistance of the pins had not yet been set high.

3.3.3.2 Temperature measurement

The four temperatures that will measured are the inlet, outlet and ambient temperature. With the exception of ambient, these will be measured indirectly by measuring the temperature of the metal pipe or tank in contact with the water. The ambient temperature will be measured by a temperature sensor external to the enclosure containing the controller to avoid reading an ambient temperature elevated by heat emitted by the electronic components.

Temperature measurement can be loosely classified as falling in one of three categories; thermometers, probes and non-contact [21]. Thermometers use thermal expansion to produce a physical change with temperature. Non-contact sensors are primarily optical in nature and measure the heat that is emitted as radiation by an object. The electrical characteristics of probes change in proportional to temperature change [21].

Given that the temperatures are to be measured electronically. The most appropriate choice for the measurement would be probes. These devices themselves fall into three categories; resistance elements, thermocouples and semiconductors [21]. Semiconductor sensors were chosen because they are inexpensive and require minimal external circuitry to produce a viable signal.

Design for MkI and MkII

The sensor that was chosen was the LM35CZ by Texas Instruments. This temperature sensor was chosen because it outputs a linear scaled voltage directly proportional to temperature and requires no calibration. Power could be supplied directly from the 5V bus and the output could be measured directly by the processor. The relevant details of this sensor are shown in table 3.2.

Supply voltage	4 V - 30 V
Temperature scale factor	10mV/°C
Temperature range	-40°C to 110°C
Accuracy	0.5°C
Packages	TO-92 TO-CAN SOIC TO-220

Table 3.2: LM35 temperature sensor [20]

The sensors were attached to leads of differing lengths depending on the location that the sensor would be attached to the EWH. The TO-92 package sensor was used because the cables could be soldered directly to the leads before the whole package was sealed in heat shrink. The sensors were then further protected by being fastened to the pipes by self-adhesive silicone tape. At 10mV per °C and a range of 0 °C to 100 °C the sensors will require an an analogue to digital input with a range of 0V - 1V.

Re-design for MkIII

For MkIII the 5V rail was omitted from the design to reduce complexity. Therefore, a linear semiconductor temperature sensor that could be powered from the 3.3V rail was sourced to replace the LM35 from Texas Instruments.

3.3.3.3 Relay activation measurement

A need was seen for feedback from the relay switching the thermostat controlling the element of the EWH. Leaving the thermostat in the loop adds an additional layer of safety to the controller and will not render the EWH uninsurable or void the warranty. However, the presence of the thermostat means that the state of the relay cannot be determined from the power measurement. The control system would be unable to determine if the thermostat is off due to the temperature of the water or the relay failing to switch. In this case diagnosis of a failed relay would only be determined by the user receiving cold water from the tap several hours later. This would be highly inconvenient for the user and could result from something as simple as a dropped communications packet.

Design for MkI and MkII

A circuit was designed to monitor the Normally Open connection of the relay for the presence of a 220V AC signal. To isolate the low voltage side of the circuit from the 220V AC mains an opto-isolator was used. The 4N35 opto isolator from Vishay was used.

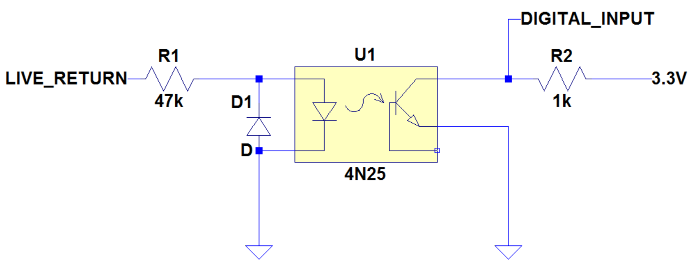


Figure 3.9: Relay activation feedback circuit

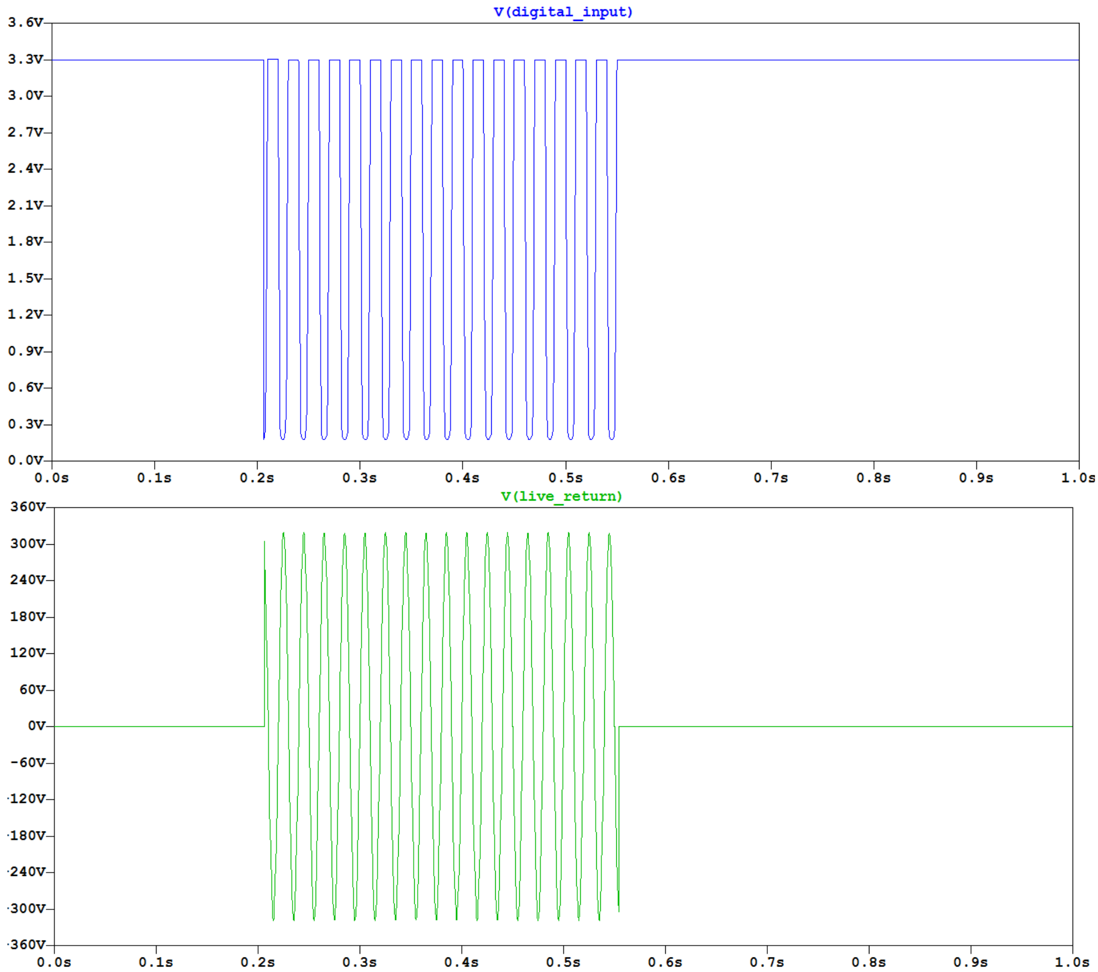


Figure 3.10: Simulation results for relay feedback circuit

The internal diodes have a maximum forward current of 50mA and a maximum reverse voltage of 6V. Similar opto-isolators have a minimum forward current of 5mA. This was considered in calculation in order to allow alternate components to be used. A diode was used to limit the reverse voltage and a resistor was used to limit the current through both the opto-isolator and the diode. The value of the resistor was calculated as follows. The final circuit is shown in Figure 3.9.

$$I_{opto_Max} = 50mA \tag{3.10}$$

$$I_{opto} = \frac{V_{peak}}{R} \tag{3.11}$$

$$\therefore 50mA > \frac{V_{peak}}{R} \tag{3.12}$$

$$\therefore R > \frac{320}{0.05} \tag{3.13}$$

$$R > 6k4\Omega \tag{3.14}$$

$$I_{opto_Min} = 5mA \tag{3.15}$$

$$\tag{3.16}$$

R was therefore chosen as 47kΩ. This design was used for MkI and MkII.

Simulation of MkI and MkII design

An LTSpice simulation of the circuit shown in Figure 3.9 was done to verify the design. The results can be seen in in Figure 3.10. The results from this simulation were used to to inform the programming of the algorithm used to update relay status. A flag was set in software every time a falling edge was detected from the output of the detection circuit. This flag was reset five seconds before the status message was sent to allow it to be set again if the relay was indeed closed.

Problems with MkI and MkII design

The waveform shown in 3.10 was found to be problematic in that it added complexity to the firmware written for the micro-controller. The chosen input for the micro-controller had to be capable of receiving interrupts a minimum of 50 times a second, one for each falling edge. The waveform shown in 3.10 both rises and falls when the relay is active. This meant that the interrupt would trigger repeatedly while the relay was active and not trigger at all when it wasn't. This required code to be written to reset the "Relay Closed" flag set by the interrupt after a given time-out.

Re-design for MkIII

The relay detection circuit was redesigned for MkIII to reduce the required firmware complexity and micro-controller requirements. The output was moved to measure at the collector of the photo-transistor. This provided a positive signal to which an RC filter could be applied. An AC input from Fairchild semiconductor was used to eliminate the need for the protection diode and to reduce the requirements for the filter by doubling the frequency. The photo-transistor requires has a VCE_{sat} voltage of 0.4 and a maximum

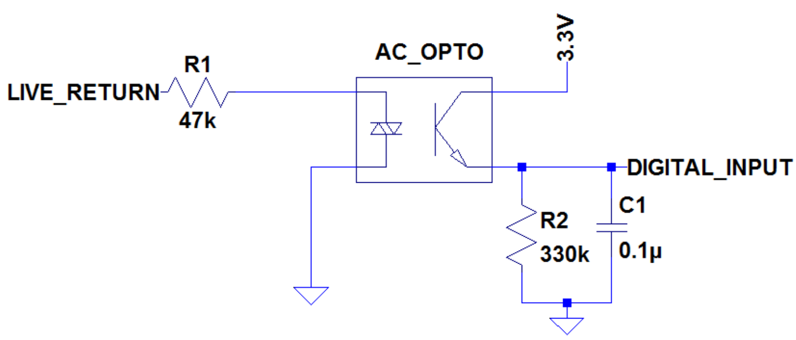


Figure 3.11: Redesigned relay feedback circuit

required input voltage of 1.5V. Voltage ripple and RC values were calculated as shown by modelling the output of the photo-transistor as a half-shifted square wave.

$$RC >> \frac{1}{f} \tag{3.17}$$

$$f = 2 \times 50 \tag{3.18}$$

$$\therefore RC >> \frac{1}{120} \tag{3.19}$$

$$C \text{ is chosen as } 100nF \tag{3.20}$$

$$R >> 83.3k\Omega \tag{3.21}$$

$$\therefore R \text{ was chosen as } 330k\Omega \tag{3.22}$$

$$V_{ripple} = \frac{V_{peak} \times t_{ripple}}{RC} \tag{3.23}$$

$$V_{peak} = 3.3 - VCE_{sat} \tag{3.24}$$

$$t_{ripple} = arcsin\frac{3}{320} \times 200\pi \times 2 \tag{3.25}$$

$$\therefore t_{ripple} = 1.7ms \tag{3.26}$$

$$\therefore V_{ripple} = 0.15V \tag{3.27}$$

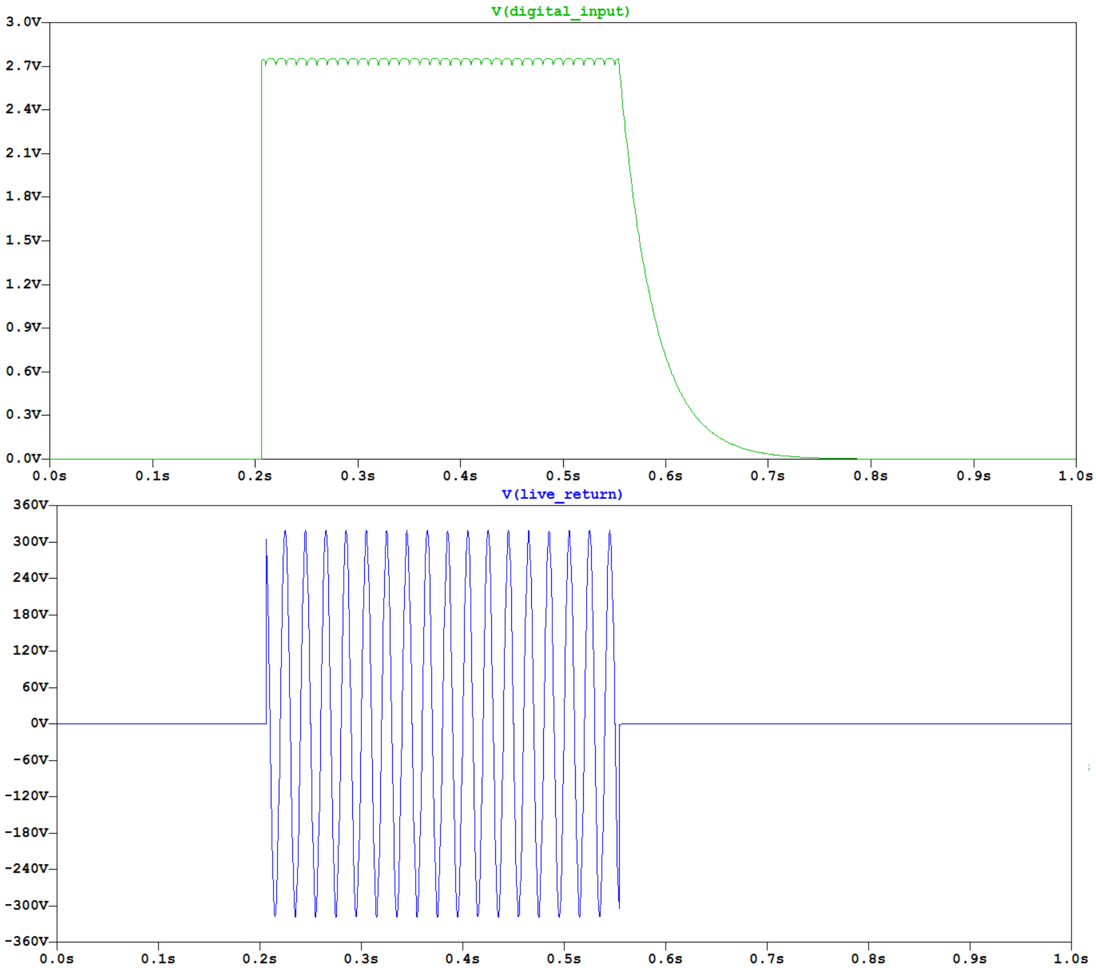


Figure 3.12: Simulation results for redesigned feedback circuit

Simulation of MkIII design

The redesigned circuit was simulated in LTSpice. The resulting circuit and waveform can be seen in figure 3.11 and 3.12. It can be seen that the result for V_{ripple} is borne out in the waveforms produced by the simulation. This output will produce an interrupt when the relay is both closed and opened and can be polled instantly to determine the current state of the relay.

3.3.4 Power measurement

Power measurement was implemented to enable the an accurate measurement of the power consumption of a geyser to be recorded. To accurately measure power consumption two of three values are needed; voltage, current and resistance.

Design for MkI and MkII

As in [17] a purpose designed Power Measurement IC (PMIC), Figure 3.13, was used to measure the power in MkI and MkII. The only difference in the circuit implemented in this system was that a smaller form factor current transformer was used and the burden resistors where adjusted to allow for the greater currents that were switched. Voltage and current measurements were obtained from voltage and current transformers to maintain isolation of the circuit.

Problems with MkI and MkII design

The PMIC circuit adds complexity to the controller and was found to occasionally require a reset if incorrect instructions were sent to the device. Further, it made use of three of the pins of the micro-controller: two for the serial communications and one for

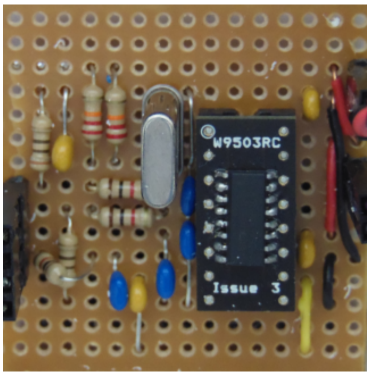


Figure 3.13: PMIC circuit

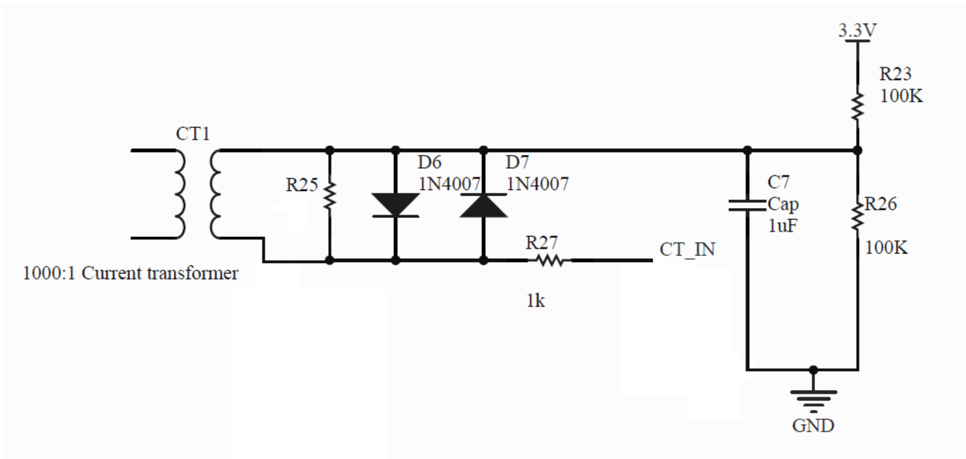


Figure 3.14: Current input biasing and protection circuit

the reset line.

Re-design for MkIII

To reduce the complexity of the circuit the PMIC was replaced with a single current reference. This reference can then be used with a fixed RMS voltage value to calculate the power directly. To measure accurately and still remain electrically isolated from the 220V mains supply a 1000:1 current transformer was again used. The Analogue to Digital Converter (ADC) of the micro-controller cannot read negative values and will be damaged if the input exceeds 3.3V or falls below zero.

The output of the current transformer was therefore made to oscillate around a voltage reference of 1.65V. Further, to protect the micro-controller inputs the outputs were clamped to one diode drop above and below the reference voltage. The current transformer used has a ratio of 1000:1. The maximum element power that the unit has been designed for is 4kW. A 4kW element draws approximately 25.7A peak current. Therefore the circuit was designed for an output of 25.7mA peak from the current transformer. The input swing is

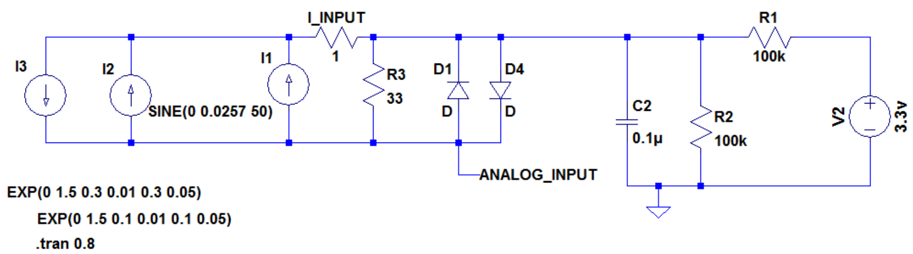


Figure 3.15: Current input biasing and protection circuit simulation model

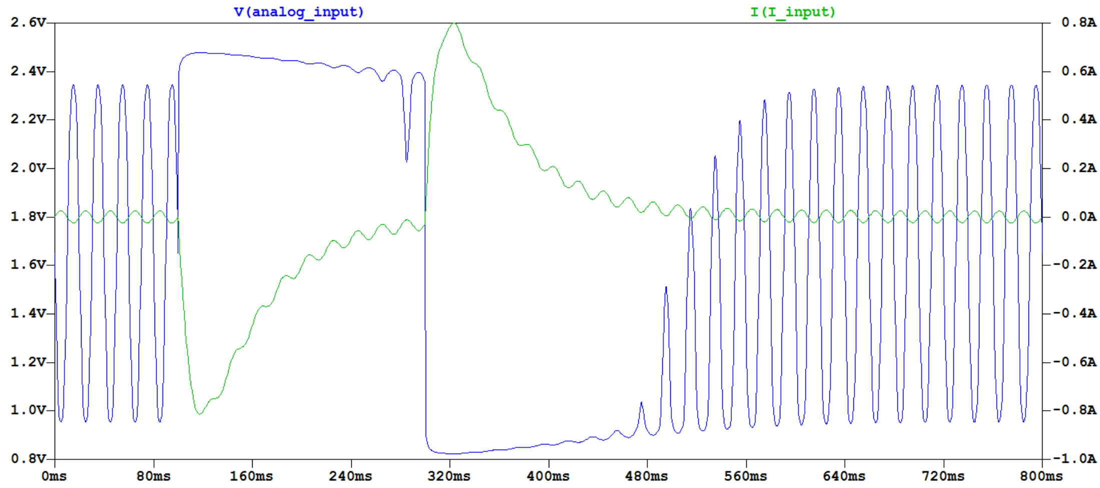


Figure 3.16: Simulation results current input circuit

a diode voltage drop of one volt above and below the reference.

$$V_{Diode} = 1V \tag{3.28}$$

$$I_{Peak} = 25.7A \tag{3.29}$$

$$\therefore I_{PeakCT} = 0.0257A \tag{3.30}$$

$$V_{Diode} > I_{PeakCT} \times R \tag{3.31}$$

$$\therefore R < \frac{V_{Diode}}{I_{PeakCT}} \tag{3.32}$$

$$R < 38.91\Omega \tag{3.33}$$

Therefore the value of R25 was chosen as 33Ω to prevent the input from clipping.

Simulation for MkIII design

The current input circuit was modelled in LTSpice as shown in Figure 3.15. Positive and negative input transients were simulated to determine whether the input would stay clamped to the reference. As shown in Figure 3.16 if positive or negative transients, even in excess of 0.8A, are experienced at the output of the current transformer, the input to the micro-controller will be held to between 0.8 and 2.6V.

3.3.4.1 Water meters

Water consumption measurement was implemented to allow accurate water consumption tracking and event detection. Hot water flow was measured at the input to the EWH because heated water would degrade the plastic internal mechanisms of mechanical meters, even if the bodies of these meters were constructed of metal. Two water consumption measurements were taken, one at the input to the EWH to measure hot water use and one measuring cold water consumption that occurs inside the home. This measurement was intended to be taken where the cold water supply branched off from the supply taken

Figure 3.17: Elster volumetric water meter

to the EWH after passing through the pressure reducing valve. This provided the added safety of limiting the pressure experienced by the water meters. Water supply systems in this form are known as balanced. This means that the hot water pressure and the cold water pressure are the same. In practise, few houses were found to be implement this standard. In these houses the cold water measurement was not taken.

Design for MkI and MkII

For MkI and MkII volumetric flow meters with a rotating impeller were used. The impeller was attached to a magnet. The changing magnetic field is detected by an integrated hall effect sensor. This sensor output 750 pulses per litre. This allowed high resolution water measurements to be taken. The sensor required a supply voltage of 4.5V and output a signal that was fed directly into the input protection circuit. The pulses were counted by an interrupt service routine on the micro-controller.

Problems with MkI and MkII design

Several problems were experienced with the flow meter. The impeller was responded to flow in both directions. This meant that small backward flow of water due to thermal expansion was detected as water consumption. Further, the devices were not approved by standards and the pulses-per-litre had to be determined experimentally. Finally, the small orifice resulted in one user complaining of reduced flow rate.

Redesign for MkIII

For MkIII the water consumption measurement was redesigned to resolve the problems found with the previous water meter. An additional factor that was addressed was the removal of the 5V rail supplying the sensors. The new water meter therefore needed to be able to be supplied from the 3.3V supply. For these reasons the Elster Kent V100T PSM Volumetric Water Meter was chosen, Figure 3.17. It is pressure rated for residential use, is certified to be accurate to within 2% at the flow rates we will be experiencing, SABS approved, and resistant to reverse flow. Digital indication of the measurement is provided by means of a reed switch activated by a magnet within the body of the unit. The reed switch will close once every half litre.

3.3.5 Leak detection

The sensor for the leak detection was placed in the drip tray of the EWH. This enabled it to detect leaks occurring over the whole body of the EWH.

Design for MkI and MkII

A simple conductive sensor was used to detect the presence of liquid in the drip tray. The sensor consists of two probes and biasing resistors as shown in Figure 3.18 which was used in MkI and MkII. The voltage detected on the signal line would be zero until the two probes were immersed in water, at which point the circuit would be completed an the voltage detected by the sensor would increase. The primary problem with using immersed conductive probes to detect the presence of water is that the probes degrade as electrolysis occurs between them. This was not an issue in this case due to the fact that the probes would not be in contact with the water in normal operation. The value for R_{Water} used in Figure 3.18 was determined experimentally.

Problems with MkI and MkII design

The probe leak detector used for MkI and MkII experienced several problems. The most serious of which was that the biasing resistors were all located on the sensor end of the cable which left cable susceptible to electro magnetic interference (EMI). This, coupled with the low threshold voltage resulted in false positives in certain instances. In one in-

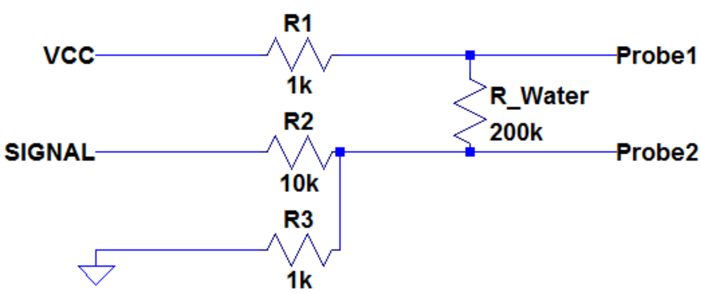


Figure 3.18: Conductive leak detector circuit

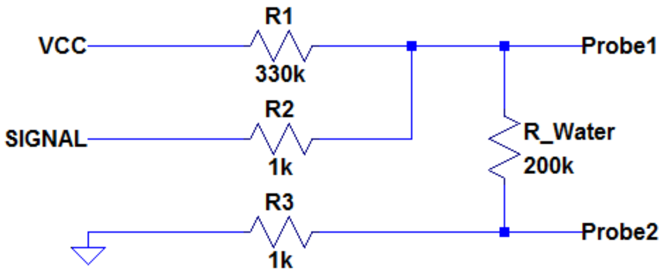


Figure 3.19: Redesigned conductive leak sensor

stance a a user's security system radio transmitter was found to trigger the drip detection.

Redesign for MkIII

For MkIII the system was redesigned to eliminate false positives. The biasing resistors were moved from the sensor itself onto the control board to remove the effect of EMI. An error integrator was implemented in the firmware of the device and the biasing resistors were revised to create a larger output swing. The resulting circuit is shown in Figure 3.19.

3.3.6 Actuation

The EWH controller was designed to control the water supply and the power supply to the EWH. Power was controlled to allow temperature control to be implemented based on feedback from the temperature sensors. Further, the water supply should not be shut off without cutting power to the device. Water supply was controlled to allow the controller and the user to react immediately to the detection of a leak.

Figure 3.20: Latching relay

3.3.6.1 Power Control

The actuation method chosen for the EWH would be required to repeatedly switch currents of up to 20A while consuming minimum power itself. Three methods of controlling the power supply to the EWH were investigated; relays, solid state relays (SSRs) and latching relays. Relays were discounted because the constant power that they would draw while switched would increase the requirements of the power supply circuit and the power consumption of the controller. SSRs require very simple switching circuits and have extremely low power draw, comparable to that of an LED. The disadvantages of SSRs are their large footprint and the expense, both of which are increased when the required heat-sink is added.

For these reasons a switching relay was chosen and used in all iterations of the design; MkI, MkII and MkIII. The state of a switching relay is persistent and is changed by the application of a pulse to the inputs. The switching relay chosen for the controller, as shown in Figure 3.20, is rated to switch 50A and requires an 50 millisecond pulse at 12V to either the set or reset pin to close or open the relay.

A simple transistor circuit was designed to enable relay switching by the micro-controller from the unregulated 16V supply and is shown in Figure 3.21. The coil of the relay is rated for a nominal supply voltage of 12V, for this reason R35 was included to limit the current through the relay coil. The circuit shown in Figure 3.21 performed well in tests and in the field trials and was used in all the iterations of the hardware, MkI, MkII and MkIII.

3.3.6.2 Water supply control

The water control would be used to shut off water flow if a leak was detected by the system. Additionally the user would be able to activate it manually to limit damage or

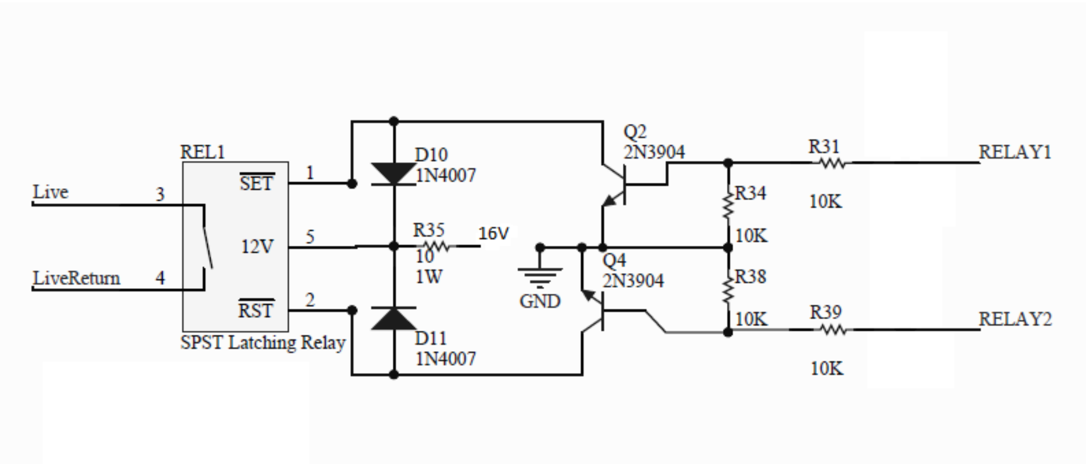


Figure 3.21: Latching relay control circuit

Figure 3.22: Aquanet Plus latching valve

wastage if a leak were to develop at a point of use e.g. a tap or shower-head or to do maintenance on the EWH. In the event of a leak developing or maintenance needing to be done the user would need to be able to shut-off power to the device without the water control deactivating.

The typical way to achieve this would be with the use of a normally closed solenoid valve. If the valve were closed it would remain so if power was removed. The problem with this as a solution is that a normal power outage would also cut off a person's water supply. Additionally, a solenoid valve consumes a considerable amount of power and generates a great deal of heat if energized for a long time. For the system to fail safe as described above the valve would be energized almost continually.

For these reasons a latching valve was used. The state of a latching valve is persistent and requires a short voltage pulse to switch. The polarity of the pulse must be reversed to either open or close the valve. Instead of a solenoid, latching valves make use of a persistent mechanical system, such as a DC motor drive, to open and close the pilot valve. The Aquanet Plus latching valve by Netafim was used in this project for all iterations of the hardware. It is rated for pressures of up to 10 bar and requires a 12V

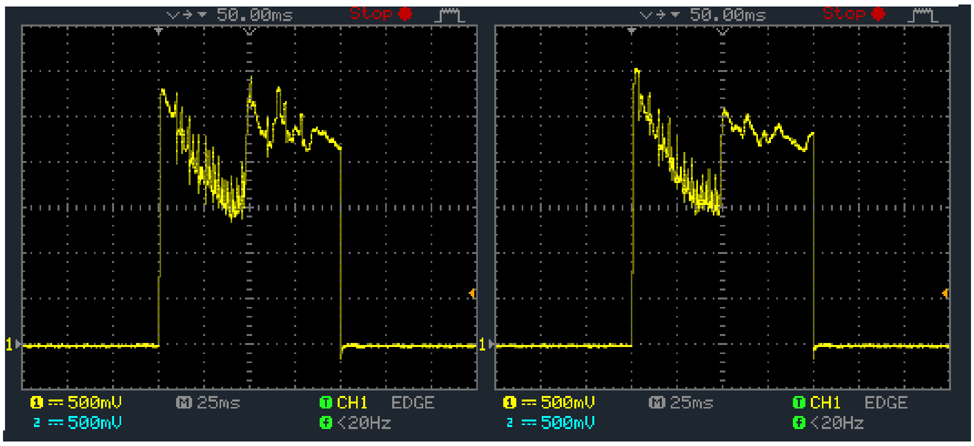


Figure 3.23: Latching valve current switching profiles. Left: Open. Right: Close

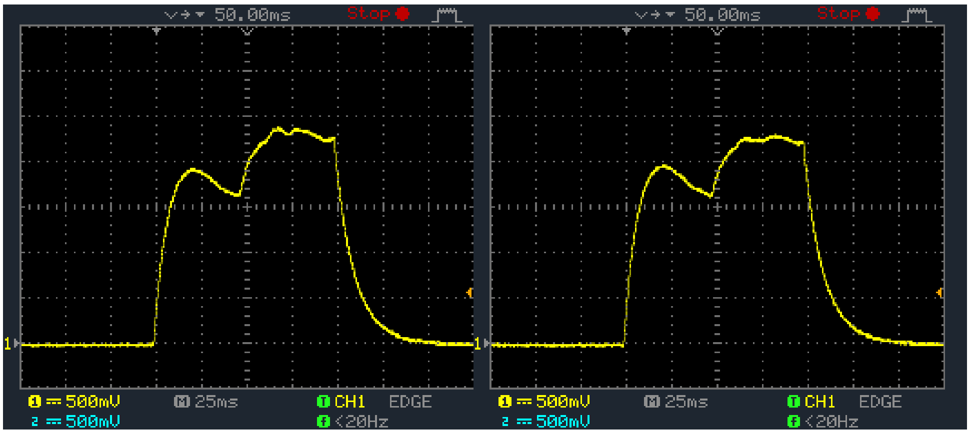


Figure 3.24: Filtered latching valve current switching profiles. Left: Open. Right: Close

pulse of 80ms to open or close.

In an effort to provide some feedback about the switching progress the current profiles of both open and close latching events were recorded. This was done by using an H-bridge with an integrated current reference to switch the valves. The resulting profiles, shown in Figure 3.23, were too noisy to use draw conclusions from so they were filtered using a passive RC filter. The profiles of the current use after being filtered are shown in Figure 3.24 From these profiles it could be seen plainly that open and close events were identical from an absolute current consumption point of view. While completely different signals are required to open and close the valve it would have provided a useful check for correct installation, positive and negative leads of the valve reversed for instance.

The current was noticed to increase just after the unit had completed switching due to the internal rotor locking. It was hypothesized that this could provide an indication of when the latching valve had completed switching. An analogue comparator was attached

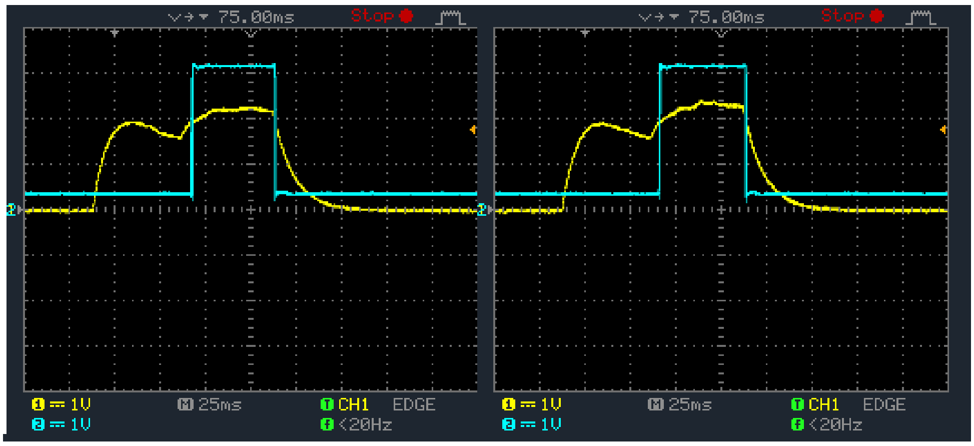


Figure 3.25: Latching valve current switching profiles (Yellow) with comparator output (Blue). Left: Open. Right: Close

to the output and tuned to trigger when the current increased after the valve had finished switching. As seen in Figure 3.25 the system worked as expected after the reference for the comparator had been set to 2V. It was found that the peaked at approximately 2.7A. Taken across a 1Ω reference resistor this resulted in a peak of 2.7V. Once filtered the output peaked at 1.9V while switching and rose to above 2.4V after switching had completed.

The current reference was not implemented for switching detection in any of the iterations of the board, although it was retained as an option for evaluation purposes on both MkI and MkII. This was because a false positive from the comparator would result in the valve being in left half-open. Further, as shown by Figure 3.23 the valve has switched completely within 50ms. The pulse lasts a full 100ms, 20ms longer than the manufacturer specified 80ms. Further, the activated state cannot be determined from the profiles and this method is unable to provide feedback about the current state without the valve being activated.

Design for MkI

An H-bridge was used to provide the dual polarity switching pulses for the latching valve. An H-bridge is the common term for an arrangement of four transistors that is frequently used to supply to power to a DC motor at two different polarities from a single supply. This allows the motor to be operated in both forward and reverse or braked depending on which of the transistors is activated.

The H-bridge chosen for for use in MkI was the A3953 by Allegro Microsystems. It is suitable for switching supply voltages of up to 40V at 1.3A. It includes a current reference that was used for the current analysis of the latching valve [22]. Finally, it was available as a 16 pin DIP which both was ideal for prototyping and would keep the form factor of the completed PCB to a minimum.

Problems with the MkI design

Several problems were found with the design used in MkI. First it was discovered from the tests that the current supplied by the A3953 was peaking at approximately 2.7A. This greatly exceeded the given absolute maximum supplied current. Even in the short on-periods of 100ms this excess current caused the IC to overheat. If the program were to stall during a latching operation the A3953 would burn out and need replacement. Finally, production of the A3953 has been discontinued as of 2012 [22].

Design for MkII

The choice of H-bridge was revised for MkII. The A3953 was replaced with the L6203 by STMicroelectronics. The L6203 is capable of supplying a peak current of 5A and a 4A RMS. It has built in thermal protection and a current reference output for current profiling. Finally, The logic inputs are TTL compatible, enabling them to be switched directly by the micro-controller and it requires a minimum of additional components both of which reduce circuit complexity [23].

Problems with the MkII design

Given that current profiling was not implemented as a feature in MkII, the high cost of the L6203, relative to ICs that did not have current reference outputs, was no longer justified.

Design for MkIII

The TA8428K H-bridge by Toshiba was selected for MkIII due to its simplicity, small form factor and competitive price. The TA8428K can output 3A for 100ms and 1.5A continuously and also possesses built-in thermal protection [24].

3.3.7 Communication

Two wireless communication methods were evaluated for the EWH controller. Namely, the 802.11b/g wireless standard and General Packet Radio Service (GPRS) cellular communications.

Design for MkI and MkII

Two wireless communication methods were evaluated for the EWH controller. Namely, the 802.11b/g wireless standard and General Packet Radio Service (GPRS) cellular communications. These were implemented using the integrated CC3000 wireless module on the Core and the Maestro Evo 100 GSM modem respectively. The CC3000 is built into the Particle Core and the functions can be accessed using the code libraries available as part of the core program code. The Maestro Evo 100 was set up in auto UDP mode. In this state any data that was received over the serial line was transmitted as a UDP data packet to a set IP address. Likewise, any data received by the modem was sent via the serial line to be received by the micro-controller.

Problems with MkI and MkII design

Several problems were experienced with the Wi-Fi implementation. The connection proved to be very sensitive to signal quality and range. Signal drop-outs were frequent and often the Core would require a reset to restore operation. The CC3000 does not support SSL which means that if the user access the internet through a secure portal the CC3000 will be unable to access it. Further, the devices were to be installed in roof spaces and would therefore be very difficult to access if the user changed their Wi-Fi password or SSID.

The main drawbacks of the Maestro Evo 100 are the high cost, at more than ZAR1000.00 it accounted for almost half the cost of each controller, and the unsuitability of the design to a custom built PCB. For instance, communication with the device was via RS232 serial. Which meant that the TTL serial of the micro-controller was first stepped up using a MAX232 converter and then, on reaching the device, presumably stepped down again. Custom cables and connectors had to be assembled for each device at additional expense.

Re-design for MkIII

The u-blox LEON G100 Quad-Band GSM/GPRS Module was used in the third iteration of design. It was smaller, less expensive and easier to integrate than the Maestro while providing more features.

3.4 Firmware Design

The firmware used on MkI and MkII was written in C on the web IDE provided by Particle, the makers of the Core. At the time of writing, firmware for MkIII is being written and will be strongly based on the program structure used for the final design.

3.4.1 Initial design

The initial firmware design for MkI and MkII relied on a single loop to implement control as shown in in the simplified diagram in Figure 3.26.

This version of the firmware would continuously check if a leak had been detected, timing out once a minute to send the status to the server, receive a command from the server and implement the command. If a leak was detected the command was immediately executed with the user being updated in the next communications cycle.

The detection of a leak or closure of the water flow valve would put the controller into an override state. This state could only be reset by the user and took precedence over any other commands. This was done to prevent the EWH from being in a state where the water supply was shut off but the element was still receiving power.

Testing revealed several shortcomings with this program flow. Firstly, as mentioned pre-

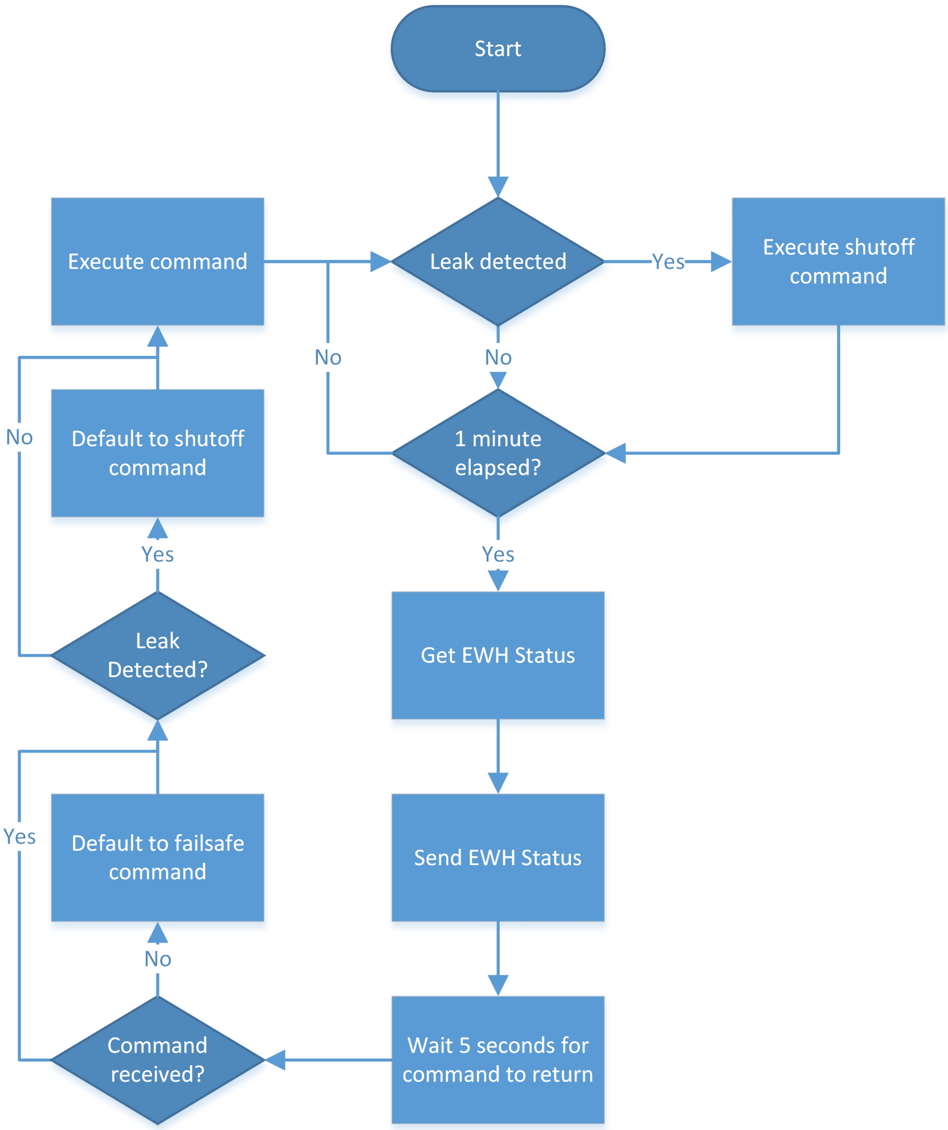


Figure 3.26: Simplified flow diagram of initial version of the firmware

viously, the low threshold of the drip sensor left it susceptible to EMI. Reading the value continuously for a single instance of the threshold being exceeded resulted in many false positives. Particularly from a unit installed in close proximity to the transmitter for an alarm system.

Further, the frequent use of delays in the code to allow the completion of certain tasks was both inefficient and blocked or delayed the execution of other, possibly more important functions. This led to intermittent errors when interrupts were triggered frequently. Finally, no provision was made for communication errors between the micro-controller and the PMIC.

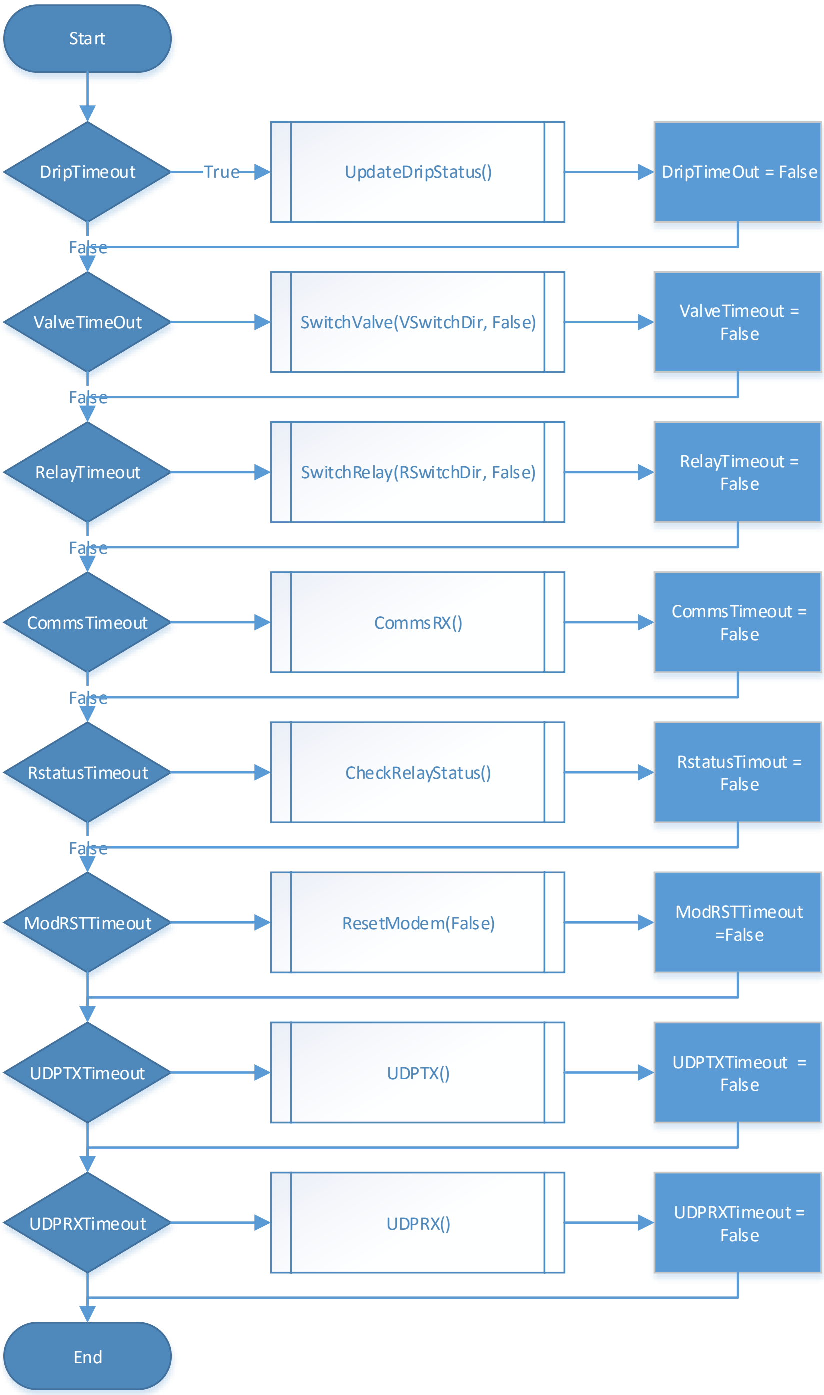


Figure 3.27: Simplified flow diagram of final version of the firmware

3.4.2 Final design

The problems with the first version of the firmware and the reliance on specialized time libraries prompted a redesign of the program flow and structure. The flow diagrams for this version of the firmware can be found in Appendix A.

The firmware is structured around time-outs decremented by a single hardware timer. This makes the code more easily portable as the user is not bound to a micro-controller with multiple hardware timers. Instead of delays being used to allow processes to take place a time-out value for the following process is set as the preceding subroutine finishes. This allows other operations to be completed in the waiting period. The simplified main loop of the rewritten software can be seen in Figure 3.27.

Chapter 4

Testing and Results

4.1 Overview

In this section performance of the EWH controller will be evaluated against the requirements as set in Chapter 3. The control units were evaluated in two stages; initially under controlled conditions in the laboratory and then in the field. The results of the field test will then be examined in more detail.

Unless otherwise mentioned the tests detailed here were carried out on the MkII controller. This was to ensure that the unit intended for field testing operated correctly and the whole system functioned as designed. Various subsystems were tested in MkI but the entire system could not be tested due to changes that were made in the design and limitations in the construction. For instance in MkI it was not possible to test power measurement over the full range because the current that could be drawn by the load was limited by the trace width on the vero-board. Finally, it was deemed important to ensure that the MkII units had been assembled correctly before they were field tested.

4.2 Tests

Before the controllers were deemed suitable for field tests they were tested under controlled conditions to determine whether they would operate correctly.

4.2.1 Power measurement test

The power measurement of the units was tested for accuracy using the Efergy, a commercial power measurement unit, shown in Figure 4.1. The PMIC used to obtain the

Figure 4.1: Commercial power measurement unit

Test number	Accuracy	Correction factor
1	91.92%	0.927
2	95.66%	1.024
3	96.19%	1.025

Table 4.1: Table showing the results of the power measurement tests

measurements uses a scaled value for both voltage and current to determine the power. This value was adjusted during testing to achieve the desired accuracy.

A variable resistive load was connected to the EWH controller and the power reading of the controller was compared to that of the Efergy commercial measurement unit. The readings were compared and the scaling factor was adjusted to increase the accuracy. The tests were conducted as follows: The variable load was adjusted through a range of power settings as the power measurement of both the EWH controller and the Efergy was recorded 25 times at set intervals. The average correction factor was determined before being applied to the scaling factor. This process was repeated three times and increased the average accuracy from 91.9% to 96.2%. This is well within the accuracy given in the requirements.

Further increases in accuracy were not feasible due to a slight non-linearity in the output of the current transformer. This was compensated for by giving greater weight to the error in the desired operating range of 2 kW to 4kW. Therefore, the accuracy will be greatest when the controller is measuring power use of the EWH element. The summarized results are shown in Table 4.1.

4.2.2 Temperature measurement test

The accuracy of the temperature sensors was tested using a digital thermometer. Two aspects of the temperature measurements were tested; the accuracy of the temperature

	Temperature			**Accuracy**		
	Actual	**Point of measure**	**Reported**	**Measurement**	**Sensor**	**Overall**
Ambient	23.8°C	23.9°C	24°C	99.6%	99.6%	99.2%
Inlet	23.7°C	24.1°C	24°C	98.3%	99.6%	98.7%
Outlet	-	50.2°C	50°C	-	99.6%	-
Internal	56.6°C	49.8°C	51°C	88.7%	97.6%	88.3%
Internal after event	54.9°C	51.8°C	52°C	94.4%	99.6%	94.7%

Table 4.2: Table showing the results of the temperature measurement tests

measurement at the chosen measurement points and the accuracy of the sensors in measuring these temperatures. Temperature measurements were taken with a digital thermometer at the measurement points and in the medium being measured. These values were then compared to each other and to those reported by the system. The results have been summarized in Table 4.2.

It can be seen from Table 4.2 that the sensors measured the temperature at the measurement points very accurately, with less than 3% error in all cases.

However, it was found that the chosen placement for the internal temperature measurement meant that the measurement error was greater than the desired 10% after prolonged periods of inactivity. This was due to the decision to measure the temperature of the EWH without compromising the structural integrity of the EWH. Surface temperature measurements were taken of the inner tank. Without adequate insulation around the measurement point, similar inaccuracy was found.

The internal temperature was measured by a sensor affixed to the outlet fitting of the EWH with the outlet temperature being measured on the outlet pipe 40 - 50cm distant from the outlet.

4.2.3 Water flow measurement test

The accuracy of the water flow measurement was assured by calibrating the flow meters by counting the number of pulses for a known quantity of water. This number was then used in the program code to calculate the number of litres that had passed through the flow-meter.

This was then further confirmed by timing how long it took to fill a container of known volume and comparing the known volume and the calculated flow rate to the values reported by the controller. The summarized results for these tests are shown in Table 4.3.

From the results in Table 4.3 it can be seen that the water volume was calculated with a maximum error of 6% which was within that specified in the requirements. What is

Volume		**Flow rate**		**Error**	
Actual	Reported	Actual	Reported	Flow rate	Volume
10	9.5	10.9	7.4	32.0%	5%
10	9.4	10.2	6.4	37.4%	6%
20	19.1	10.9	10.2	6.9%	4.5%
20	19.4	10.2	10.2	7.8%	3%

Table 4.3: Table showing the results of the water flow measurement tests

interesting to note is that all the reported values were low. Therefore the accuracy could presumably be increased by decreasing the number of pulses required for a litre in the program code. The flow rate value reported by the unit was very inaccurate for the ten litre tests. Accuracy improved drastically when the volume, and therefore duration, of the test was increased. For the increased value the result was accurate to within the desired 10%.

4.2.4 Drip detection test

The drip detection sensor was tested by immersing it in water and timing how long it took for the system to respond. The test was repeated four times each for both ordinary tap water and distilled water.

Distilled water has a conductivity approximately 400 times less than that of very pure tap water. The drip sensor was tested with distilled water to show that the system will reliably detect tap water of even abnormal purity.

In every test instance the system detected a leak and responded by shutting off both power and water supply within 9.7 seconds of immersion of the drip sensor. To increase resistance to EMI, system was designed to detect a leak only after 4 seconds of immersion. If the sensor was removed from the water immediately after 3 seconds of immersion the system did not detect a leak.

The output of the drip sensor is an analogue voltage that determined by the resistance between two probes. This voltage was measured when the sensor was immersed in tap and distilled water. The highest value output by the sensor when it was at rest was also recorded. These value are shown below.

- Tap water: 0.68 V
- Distilled water: 0.22 V
- Highest at-rest output: 0.02 V
- Software Threshold: 0.15 V

The drip sensor was found to meet the requirements set in Chapter 3 in both its response time and sensitivity.

4.2.5 Command response test

The command response of the system was tested by sending commands to the system from the website providing feedback and control. The time between the command being sent and being executed by the EWH controller was recorded. The shortest response time was 42 seconds, the longest was 102 and the average time was 83 seconds.

Theoretically, the longest possible delay is 120 seconds. This is because the communication and control loops are both triggered by unsynchronized one-minute timers.

4.2.6 Bench test

All of the MkII units that were intended for use in the field test were first bench tested. This was done by creating eight rudimentary models of EWHs using incandescent light bulbs as a heat sources as shown in Figure 4.2. This allowed visual confirmation of the state of the power control relay on the controller. On and off power control commands were sent from a simple user interface and the response of each of the controllers was confirmed visually in turn.

In this test three controller were found to switch unreliably. They were examined and the problem was traced to a resistor of incorrect value being used to limit the current through the latching relay. These three controllers had been assembled with latching relays of different tolerances due to supply chain problems. Once the resistor had been replaced with one with the correct value the test was repeated and the controllers operated as expected.

Temperature measurement was tested by affixing a temperature sensor to a steel bracket mounted near the light-bulb. The steel bracket was used to provided the sensor with thermal inertia as would be experienced when attached to a pipe. The value reported by the sensor was verified with a digital thermometer.

The power measurement of each controller was also validated in this test. Eight identical wattage bulbs were used. The power use of a single bulb was determined using the Efergy commercial meter as shown in Figure 4.3. Data from all the units was examined to establish whether they were all reporting the same value. It was found that all the controllers reported the power consumption to within 3W of the measured value of 62W. This represents an error of 5%. Which is in line with the accuracy determined in the power measurement test.

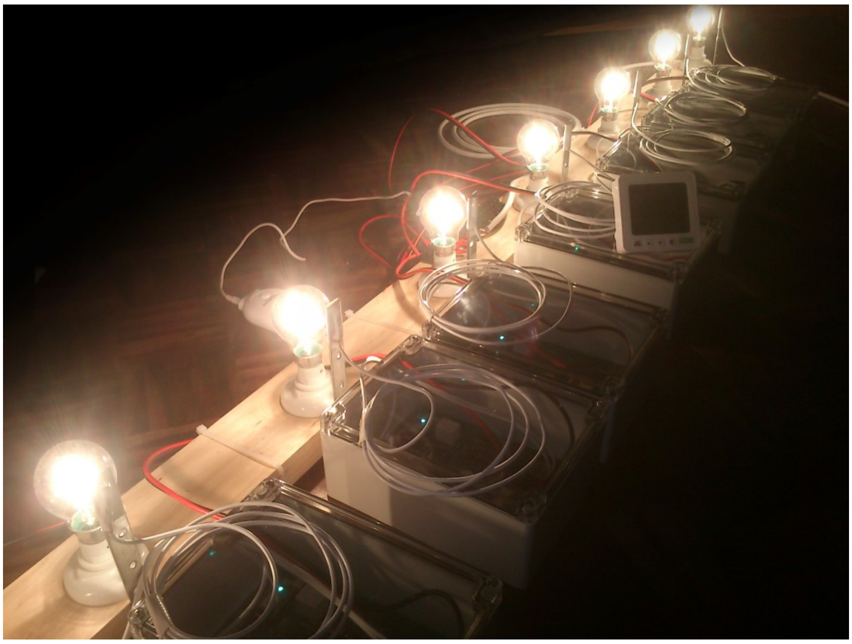


Figure 4.2: Benchtest setup

The system was then used to determine if the devices were defaulting to the default set-point control if no GSM communications were received. If the controllers maintained the set-point it would show that the was both defaulting to automatic temperature control as desired and that it was able to control temperature to a set value. The devices were set up to report data through a secondary debug interface as shown in Figure 4.4.

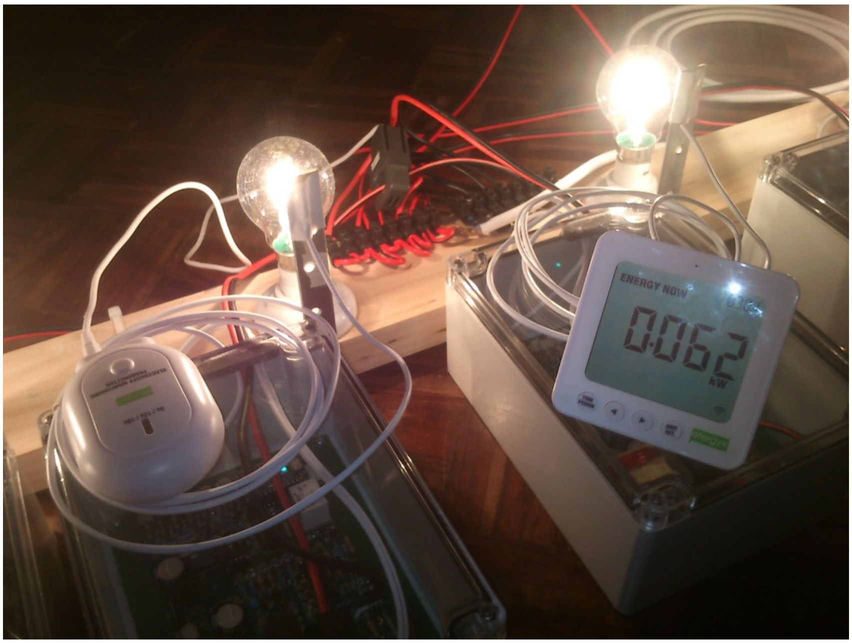
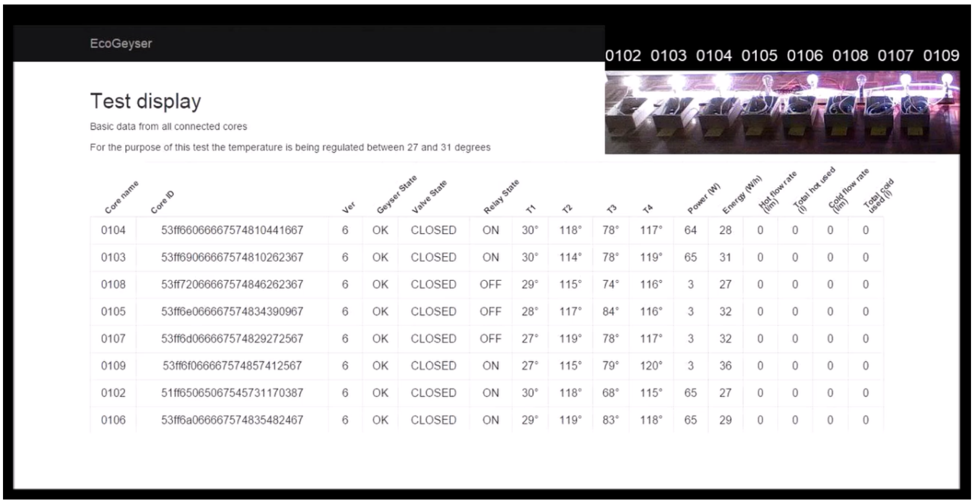


Figure 4.3: Power measurement confirmation using Efergy power meter



Test display

Basic data from all connected cores

For the purpose of this test the temperature is being regulated between 27 and 31 degrees

Core name	Core ID	Ver	Geyser State	Valve State	Relay State	T1	T2	T3	T4	Power (W)	Energy (W/h)	Hot flow rate (l/m)	Total hot used (l)	Cold flow rate (l/m)	Total cold used (l)
0104	53ff660666675748104416 67	6	OK	CLOSED	ON	30°	118°	78°	117°	64	28	0	0	0	0
0103	53ff69066667574810262367	6	OK	CLOSED	ON	30°	114°	78°	119°	65	31	0	0	0	0
0108	53ff72066667574846262367	6	OK	CLOSED	OFF	29°	115°	74°	116°	3	27	0	0	0	0
0105	53ff6e066667574834390967	6	OK	CLOSED	OFF	28°	117°	84°	116°	3	32	0	0	0	0
0107	53ff6d066667574829272567	6	OK	CLOSED	OFF	27°	119°	78°	117°	3	32	0	0	0	0
0109	53ff6f066667574857412567	6	OK	CLOSED	ON	27°	115°	79°	120°	3	36	0	0	0	0
0102	51ff6506506754573117O387	6	OK	CLOSED	ON	30°	118°	68°	115°	65	27	0	0	0	0
0106	53ff6a066667574835482467	6	OK	CLOSED	ON	29°	119°	83°	118°	65	29	0	0	0	0

Figure 4.4: Feedback from bench test

All eight units were allowed to run uninterrupted for an hour and the debug interface was recorded for the duration of the test. All eight units were found to accurately regulate the temperature to between the pre-set values of 27 and 31 degrees. A value range was given because in the EWH units the temperature would be regulated between 55 and 60 degrees. Hysteresis in the temperature control is important to prevent the relay switching too frequently and burning out.

4.2.7 Communication reliability

The reliability of UDP for communication between the server and the EWH controllers was a concern because of the fire-and-forget nature of UDP packets. To evaluate the reliability, the communications from the unit in the laboratory was evaluated over a period of two weeks and found to operate at less than 2% packet loss.

After deployment, the communication data of all the operational units was analysed over a two month period and was found to have an average packet loss of 2.34%. If the worst performing unit was removed from the set the average went to 0.94%. The lowest packet loss for a day was 0% and the highest was 18.54%.

4.3 Results

The controllers were field tested to determine if they were able to save reduce power consumption in real world scenarios. The circuit board was placed inside a drip proof enclosure to provide protection from the environment as shown in Figure 4.5.

Figure 4.5: EWH controller in enclosure

4.3.1 Laboratory test unit

Before units were deployed to test subjects' homes, a controller was attached to a 100 litre test EWH installed in the laboratory. The EWH had a 2kW element which could be safely powered from the supply available in the laboratory. The unit was used to monitor and control the test EWH for a period of approximately two weeks before units were installed in homes.

The laboratory test unit can be seen in Figure 4.6. This EWH was installed by a qualified plumber and is functionally identical to what could be expected to be found in a

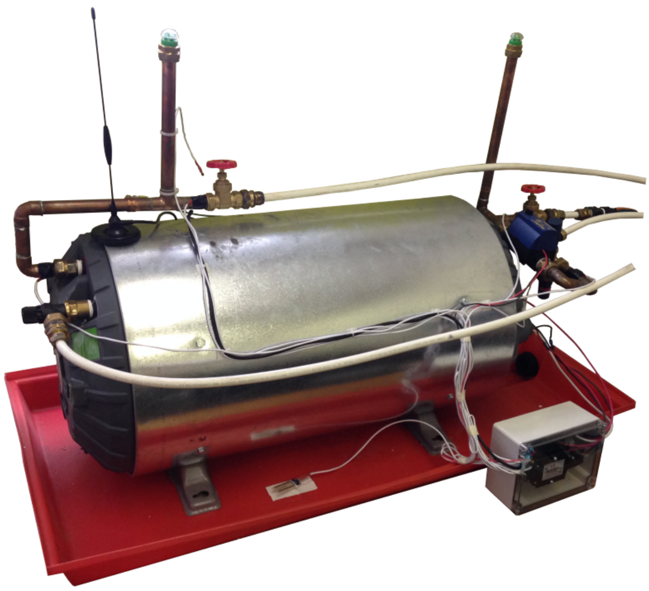


Figure 4.6: 100 litre prototype EWH installed in the laboratory

EWH ID	Capacity	Element power	Cold flow	Orientation	location
102	150	3kW	No	Horizontal	Roof space
104	150	3kW	Yes	Horizontal	Roof space
106	150	3kW	No	Horizontal	Garage rafters
107	200	4kW	Yes	Horizontal	Roof space
108	150	3kW	No	Horizontal	Roof space
109	150	3kW	Yes	Horizontal	Roof space
110	100	2kW	Yes	Horizontal	Laboratory
111	150	3kW	Yes	Horizontal	Outside
112	150	3kW	No	Vertical	Outside

Table 4.4: Table showing details of EWH installations

typical domestic installation. The only difference that was found is that the ambient temperature of the laboratory is controlled to 23 °C which is lower than the average temperature inside a roof space. Finally, all of the homes in which control units were installed had EWHs larger than 100 litres elements drawing more power than 2kW. This was not ideal but could not be remedied because of the power supply limitations in the laboratory.

The unit installed in the lab allowed tests to be run in controlled conditions without inconveniencing users. Particularly, tests involving the handling of drip detection events. The drip detection was activated by pouring water over the drip sensor and the system was observed to determine if it responded correctly. A light was connected in parallel to the element of the EWH and was used as visual confirmation of the state to which the element had been switched.

Element control commands were then sent to the unit from the web user interface to determine if the system would respond while in "EWH burst" state. The system successfully disregarded all commands until the "clear burst state" command was sent. When this command was received it correctly opened the valve and awaited further instructions.

The system was also power cycled while water covered the drip sensor and the unit was in "EWH burst" state. When power was restored to the system "EWH burst" state was cleared and then immediately set again as a result of water in the drip tray. Clearing the state when the unit is power cycled allows a user to reset a unit for which communications has failed entirely.

Finally the response of the system to a communication failure was tested by removing the antenna while the unit was operating. This would cause successive packet loss and caused the unit to default into "AUTOMATIC" state. In this state the element maintained a set point temperature of between 55°C and 60 °C. The unit was found to respond correctly after the required time out had elapsed.

4.3.2 Field tests

Eight EWH controllers were installed in homes in the Cape Town and Stellenbosch municipalities. A summary of the installations can be found Table 4.4. Each EWH was assigned an ID number to allow the data to be analysed without compromising the anonymity of the participants. As can be seen, with the exception of unit 112, all the EWH installations were horizontal.

What was immediately of interest was the discovery that of all the participants of the test group only five installations, 104, 109, 110 and 111, had balanced hot and cold water supplies. Of those five, physical constraints meant that the cold water could only be measured for three. Strangely, the balanced cold supply for 104 was presumed to supply only a single basin with the remainder of the cold supply being unbalanced.

Of all the installations that were carried out, two were rendered inoperable due to environmental factors. Unit 111 stopped operating, presumably as a result of water damage, after a thunderstorm and unit 102 was rendered inoperable due to a ripple control unit on the EWH supply.

Carrying out the installations was found to be the most onerous task of the project. Installations took between half an hour and three hours depending on ease-of-access and how the EWH had been installed. To reduce installation time for future units the power connectors of the MkIII boards were redesigned. Further, coordinating with a plumber to install the valve and flow meters proved to be a logistical challenge.

4.3.3 Data analysis

The data received from the controllers for the three month period between 15 August and 14 November was analysed to determine if the they were able to provide useful information about usage patterns for both hot and cold water and electrical power. The data was further analysed to determine the accuracy of assumptions made for ambient and inlet water temperature in previous studies.

4.3.3.1 Power use

The hourly average for power use was taken for each of the EWHs being monitored. The results were plotted in Figure 4.7. It can be seen that power use peaks at 8 AM and 7 PM. This confirms the relationship between residential water use and the morning and evening peak seen in the residential load profile. All of the units, with the exception of one, follow the morning and evening trend. The outlier, 109, follows a primarily morning usage pattern.

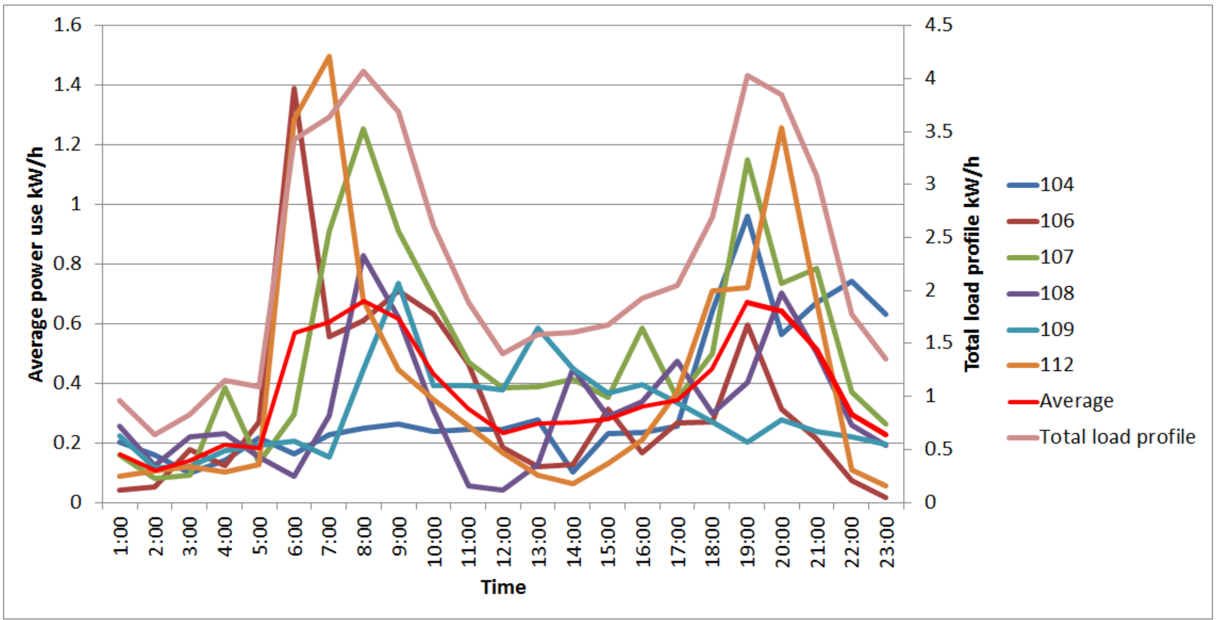


Figure 4.7: Load profiles reported by the EWH controllers

When the power use is compared to the averaged hourly maximum flow rate Figure 4.8, the effect of standing losses can be seen as the units consume power between midnight and 4 AM despite the fact that virtually no hot water is used during this period. This is further seen in Figure 4.9.

Figure 4.9 shows the average hourly cumulative hot water usage. The cumulative value for hot water use was reset each day at 2 AM. Also plotted is the typical capacity of the EWH that was seen in the study, 150 litres. It can be seen that the usage of most users

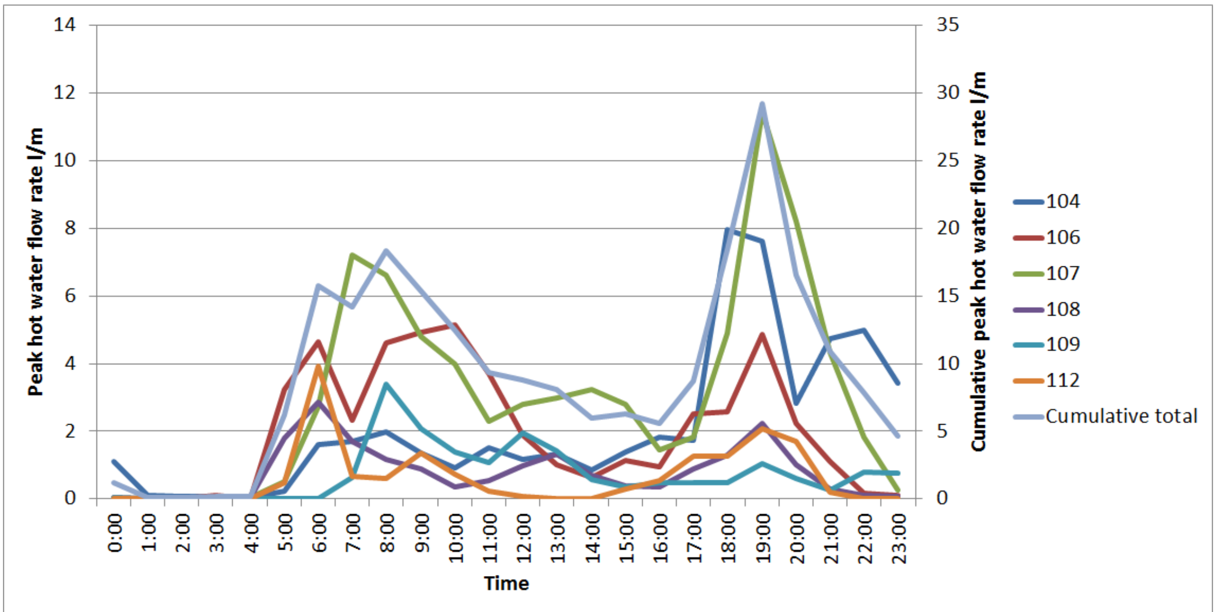


Figure 4.8: Maximum reported flow rate of hot water by time of day

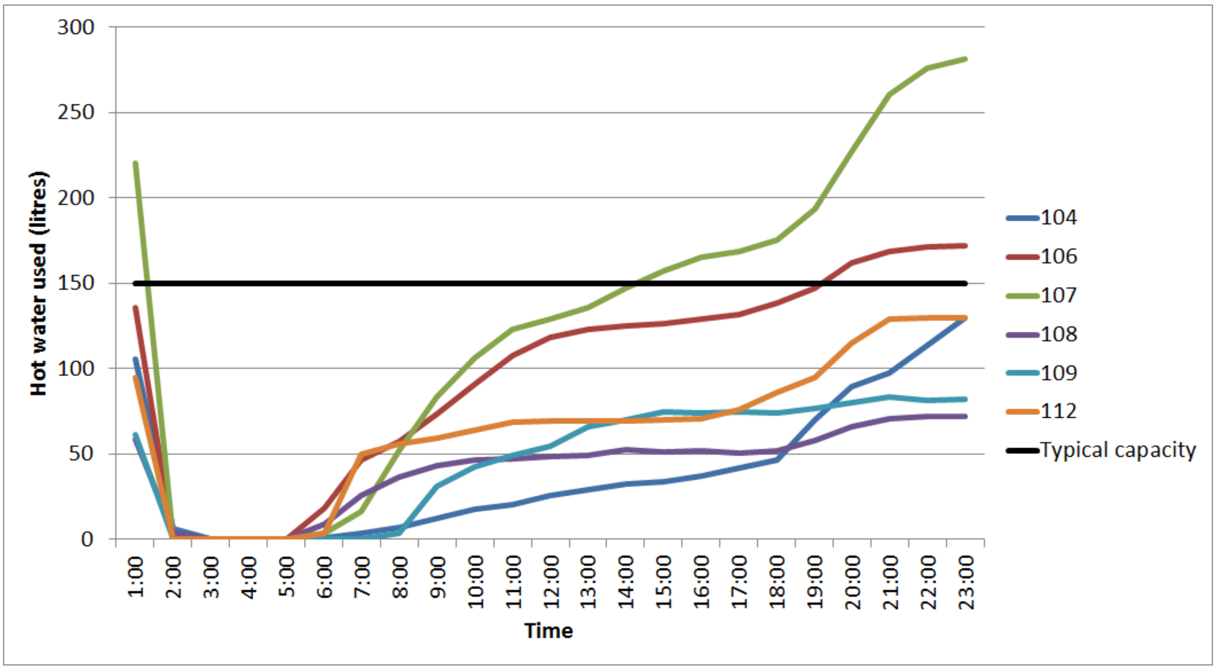


Figure 4.9: Average cumulative hourly hot water consumption

does not exceed the capacity of the EWH at all in a 24 hour cycle and it is certainly not exceeded during the morning peak. Insufficient mixing occurs within the body of an EWH over the time periods witnessed for a delayed heating cycle to have a noticeable effect on water temperature.

The energy consumption values were averaged for each day of the week and then plotted to give an indication of the users usage habits on a day-to-day basis. It can be seen from

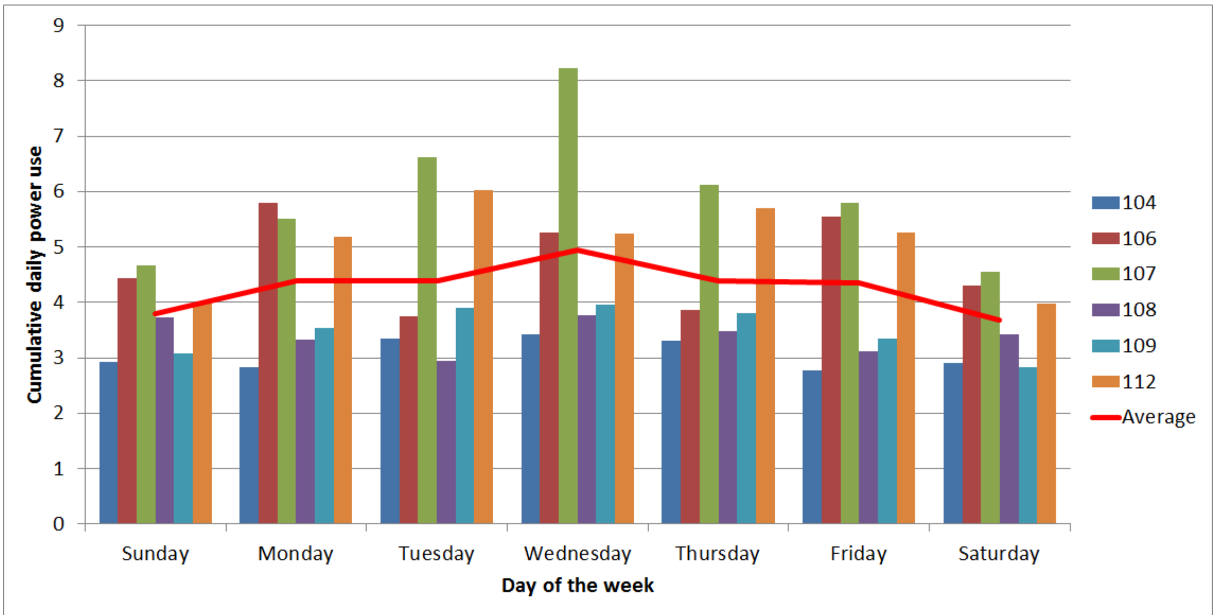


Figure 4.10: Average recorded power use by weekday

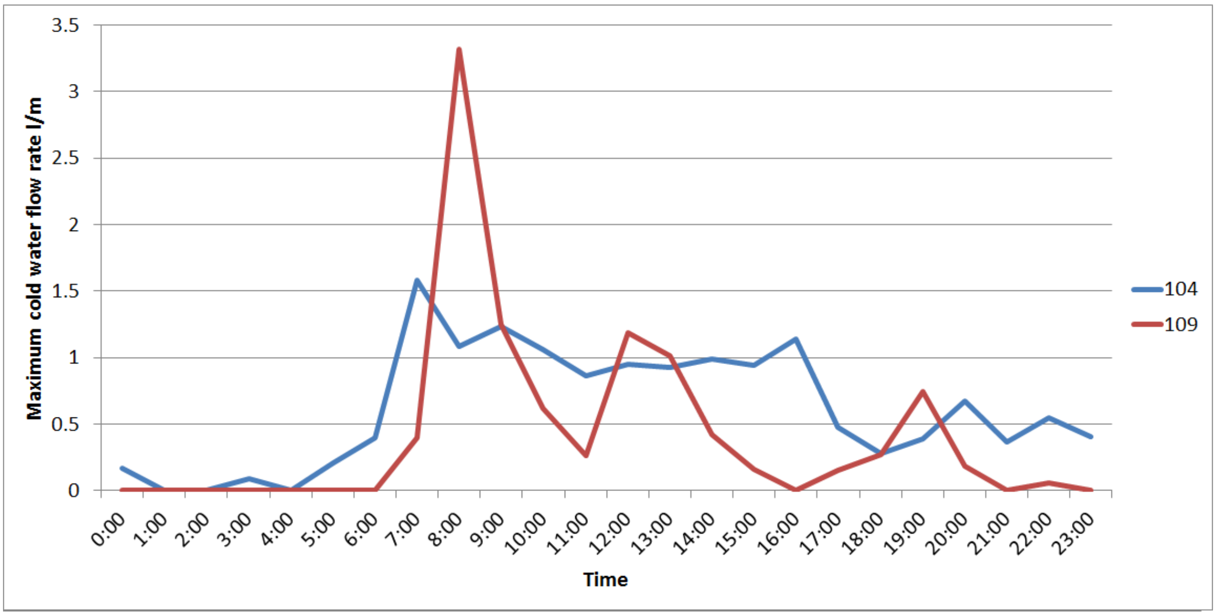


Figure 4.11: Maximum reported flow rate of cold water by time of day

Figure 4.10 that day-to-day energy consumption is fairly consistent. Energy use rises by just under 1.5kWh from the weekly low of approximately 3.7kWh on Friday to 5kWh on Wednesday. The individual consumptions are also given to show the vast difference in the daily consumptions.

The usage data of 109 can be compared directly with 112 and 104 can be compared with 104 because those pairs of households have the same numbers of occupants. The differences between these pairs is striking and serves to underline the impact of individual behaviour on consumption.

4.3.3.2 Water consumption

The highest flow rate recorded each hour was plotted for both hot and cold water use. As shown in Figure 4.8 there was almost no use between 1 AM and 4 AM. Flow rate peaked twice a day, at 7 AM and 7PM. Again it can be seen that the units with exception of 109 reported a morning and evening peak in hot water use. The peak flow rate for hot water was found to be 30 l/min and 8.4 l/min for cold water.

The cumulative total for these values fits well with both the reported and typical load profiles given in Figure 4.7 and Figure 2.10 respectively. It is significant that even a relatively small sample size gives results comparable to those seen in Figure 2.10 where over 300 different residences were analysed. It suggests that the typical use profile provides a good indication of what the usage profile of a single user can be expected to be.

When the data was plotted for cold water flow rate as shown in 4.11 the differences in user behaviour can again be seen by comparing the results to the equivalent profile in Figure 4.8. Unit 109 reported that the consumption of the user was fairly balanced between hot and cold water throughout the day. Unit 104 reported usage that varied between balanced in the morning and very unbalanced in the evening.

4.3.3.3 Temperature data

In all the previous studies that were analysed, ambient and inlet water temperature were estimated based on data from weather reports and underground water feed temperature respectively. In the mathematical analysis done in the study by Booysen et al [13] 20 °C was used for both variables.

As can be seen in Figure 4.12 the temperature for both ambient and inlet water varies throughout the day. The average values for ambient and inlet water temperature over the time period of the field study was 21.58 °C for the inlet water and 21.66 °for the ambient temperature.

The three months over which the data was received are a relatively temperate period in South Africa. This suggests that the calculated average may increase as the study continues.

4.3.3.4 Feedback experiment

Halfway into the study three selected users, 104, 106, and 107 were provided with feedback in the form a daily reports. This was done with the goal of evaluating methods of isolating the behavioural response of the a user to feedback so that the effect of implementing intelligent control could be evaluated.

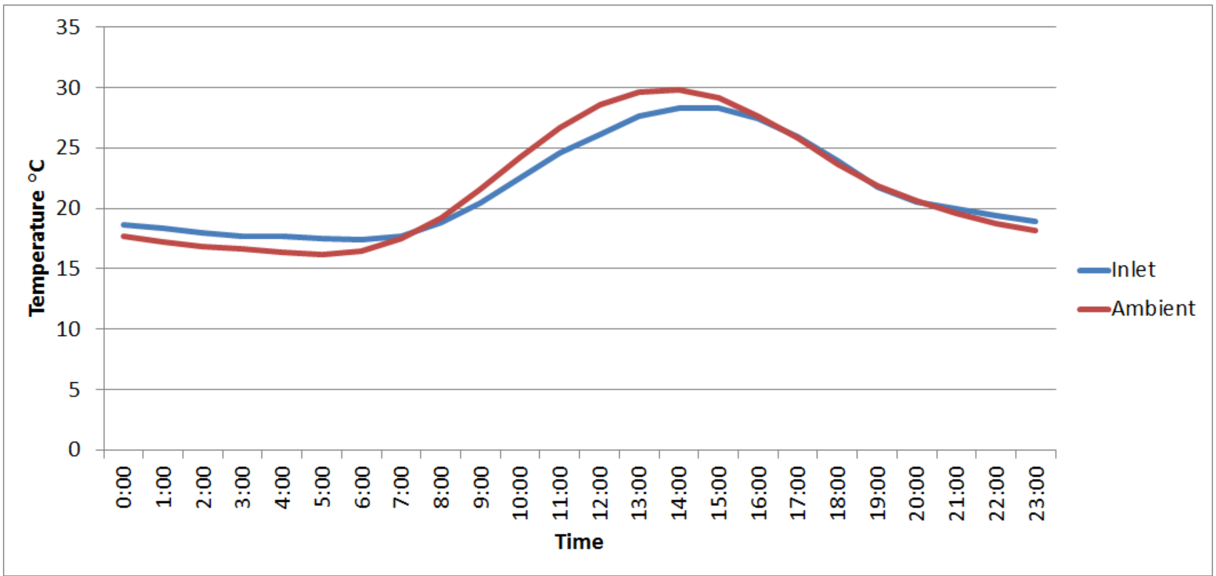


Figure 4.12: Daily inlet water and ambient temperature change

During this period the controllers were all set to maintain the internal temperature at a high set point. The selected users were then emailed reports, prepared by Cloete [25] detailing their usage for the previous day. Usage for each day was broken up into usage events. These were then divided into three groups, large, medium and small, and listed. Given with each usage event was the estimated cost and the water consumption. Users were also able to compare their usage to that of the other members of the study. The data was listed under controller number so to retain the anonymity of the users. In hindsight, this was flawed because usage was not normalized by occupancy.

The data was also made available to the users in the form of a table that attempted to convey flow rate flow rate, volume, time of event, and approximate cost to the user. This table is show in figure 4.13. Further, a table of the raw data, as shown in Figure 4.14, was provided. On this table the timing of the usage events can be easily estimated by looking at the peaks in the outlet temperature, label Far in Figure 4.14. Further, the switching of the element can be seen. Of interest are the instances, one at 1 AM and one at 4 AM, where the element switches on just to counteract standing losses.

Further study using a larger sample group will be required before any concrete observations can be made. It is suggestive, however, that the users receiving usage reports had an average power saving of 20.62% while the users who did not receive feedback had an average power saving of 13.72% in the same period.

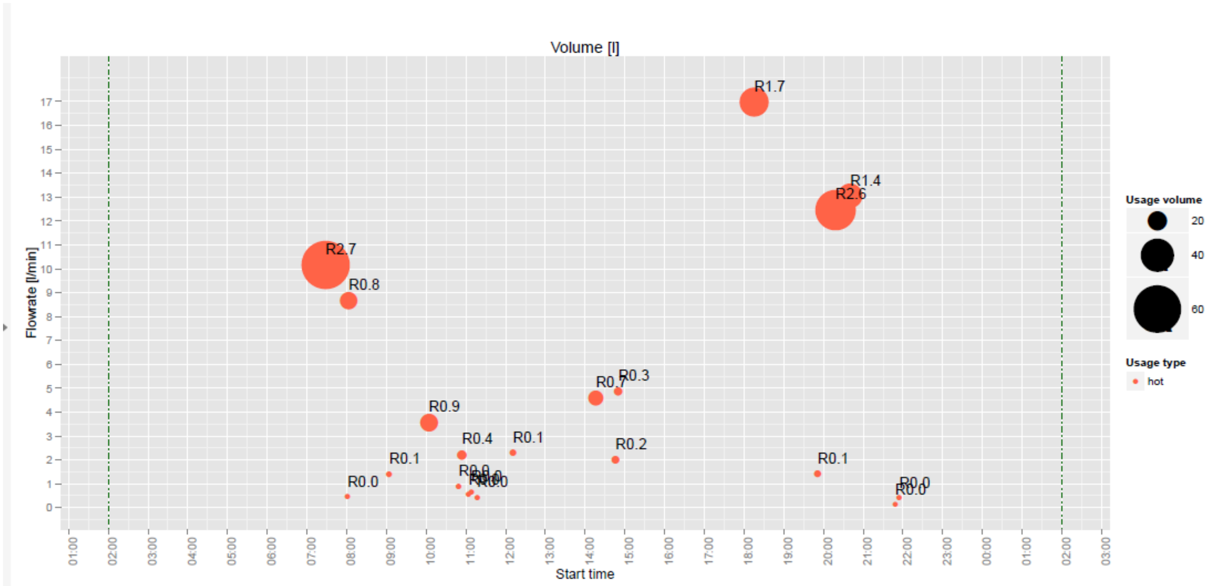


Figure 4.13: Usage data as provided to users receiving feedback[25]

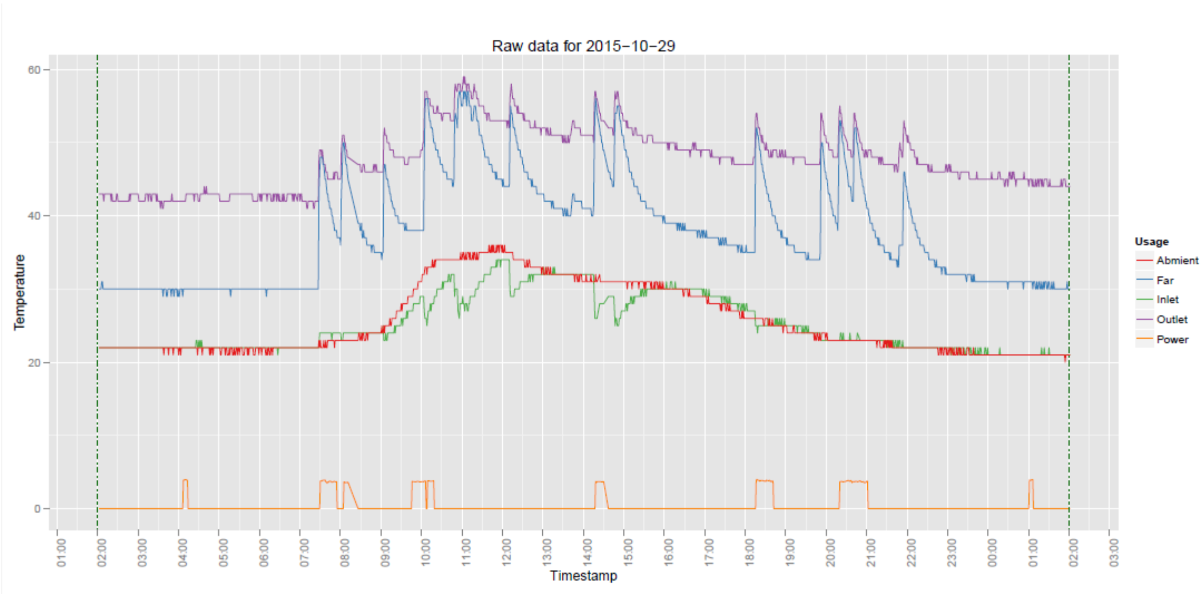


Figure 4.14: Raw data included in the daily reports[25]

4.3.3.5 Schedule control experiment

A very basic schedule control was implemented on the three units receiving feedback. The control was fixed, it was not implemented based on individual usage profiles but rather on the typical use profile. Even so the units with the control experienced an average further reduction of 5.7%. Taken over the same period, the power usage of the units not receiving feedback or under schedule control increased by 12.31%.

Again, the sample size was too small to draw any concrete conclusions but it is suggestive of power and water saving potential of informing users of their hot water use. As a result of both of the experiments one of the users experienced an average daily power consumption decrease of 48.76%.

4.3.3.6 Summary

Overall, the unit performed as expected and met the primary goal of providing data for use in the study of EWHs as stated in section 1.5. Further, the unit demonstrated the ability to implement scheduled control schemes along with the potential for these control schemes to save power.

Finally, when the data provided by the unit is disseminated to the user the results suggest a potential for power saving without any further intervention.

Chapter 5

Conclusions and recommendations

5.1 Overview

In this section conclusions will be formed based on the performance of the unit in reaching the stated goals. Recommendations will then be made for future work on the project and possible enhancements and areas for further study will be given.

Finally, a brief summary of the future work that will be done with the results the project will be given.

5.2 Conclusions

The performance of each of the subsystems that made up the EWH controller will be commented on in this section.

5.2.1 Reporting

With the exception of the internal temperature, all of the desired values were measured to within the accuracy given in the requirements. The measured values were reliably and accurately reported. Measuring the temperature on the outlet pipe was found to be an effective means of detecting events.

Measuring the temperature inside an EWH without voiding the integrity of the EWH is difficult and prone to error. The method that was used in this study was ineffective at attaining a measurement of greater than 80% accuracy.

The accurate volume measurements of hot water consumption were valuable in that they allowed total usage and usage events to be calculated accurately. It also allowed the use profile to be assembled and provided insight as to when users are using hot water.

The reported data could be successfully fed back to the user to positively affect usage. The positive results gained in the small-sample study suggest the viability of this as a means of reducing energy use. This requires a larger study group for confirmation. Further, based on feedback from the users, a better idea of what information is valued and useful in a feedback system was gained.

The data that was reported was found to be of more than sufficient resolution for user feedback and learning purposes. In many instances the data was sampled or averaged to provide the required detail without needing to manipulate thousands of data-entries. The high resolution of the data set gained from the project has already proved to be well suited for advanced analysis methods.

GSM modems were found to be preferable to Wi-Fi to establish the communication link. The primary benefit provided by using a GSM modem is the independence it provides from infrastructure at the installation site. The unit does not rely on the internet connection at the installation site, nor does the SSID and password have to be obtained from the user at installation and every time it is changed.

The on-board modem used in MkIII was found to be preferable to the separate unit that was used in MkI. The smaller footprint, reduction in complexity and reduced power requirements of the u-blox module made it more suitable for the task that the Maestro Evo 100.

In terms of communication protocol, UDP has been found to be a simple, low bandwidth, and effective communication method. The packet loss was low enough to be negligible.

5.2.2 Control

The aspects of the EWH that were controlled were water supply and power supply. The latching valve and relay used to implement the control performed as expected.

The latching valve was an ideal choice because it allowed the water flow to be controlled even when the power was cut off, without the high current draw and heating problems of a more traditional solenoid valve. This allowed the power draw of the valve to be all but ignored when the power supply of the unit was designed.

The fact that there was no feedback from the valve informing the controller of its current state meant that the firmware for the controller had to be carefully written to keep track of the state of the valve at all times. This was workable but not ideal as it is conceivable that if the valve was prevented from switching the program would assume that it had and the EWH could be heated while the inlet was closed.

The latching relay that was used to control the power proved to be the ideal low-power solution. With zero current draw after switching the relay could be efficiently used in either the off or on position for extended periods of time. With feedback from the live pin the state of the relay was always known.

The system found to be capable of implementing schedule control schemes to save power.

5.2.3 Remote

Embedding commands in the acknowledgement to a UDP packet was found to be a simple and highly effective method of implementing control. It eliminated the need for an APN to be set up.

The response time to commands sent via this method of communication was found to be adequate. At under two minutes the response time was near enough to real-time when interfacing with an EWH. The response time can, and would need to be, improved if the current form of communication were to be used with a different device.

5.2.4 Risk management

The risk management subsystems were found to function as expected. A conductive drip sensor was found to be a simple and effective method of detecting water even of abnormal purity.

Latching valves were found to be the an ideal method of cutting water supply in the event of a EWH failure. The fact that they maintain their state when the power is cut made them preferable to solenoid valves.

5.3 Recommendations

Observations made by the author and recommendations for future work will be described in this section. Further, problems that were encountered in the course of the project will be described and possible solutions will be given.

5.3.1 Reporting

The internal temperature sensor was not accurate enough to be used to control the temperature accurately. To improve the accuracy of an externally mounted internal temperature sensor it could be calibrated using the thermostat. If the thermostat is set to a single specific temperature for all the EWHs to which the controller is attached, a simple algorithm can be used to detect when the current drawn by the element falls to zero. At this point the algorithm can scale the value reported by the outlet temperature to the value to which the thermostat is set.

A different reference point for the internal temperature sensor could be found, along with more effective means of insulating the sensor from the ambient temperature. Possible locations that could be evaluated to determine if they would provide a more accurate measurement are the faceplate of the EWH, between the insulating foam and the internal tank of the EWH or beside the existing thermostat probe. In the case of the faceplate measurement the sensor will need to be epoxied to the faceplate to provide a good thermal bond.

Alternately, the internal temperature sensor can be omitted entirely in favour of using the thermostat as the internal temperature reference.

To save time during assembly and installation pre-assembled snap-on sensors should be sourced. These will cut down labour costs for the assembly and will make installation quicker and easier. It will also ensure that each sensor installation is more nearly identical to all the others.

In contrast to the internal temperature sensor the outlet sensor is both accurate and useful for both the calculation of usage events and the energy cost of those events.

The algorithm that is used to determine energy use based on volume and temperature should be developed and expanded to calculate how long the element should be energized for. The viability of treating the control of an EWH as an energy level maintenance problem instead of a temperature control problem should be evaluated.

A flow rate slightly exceeding the maximum flow rate for the water meter occurred during the field test. If that was not an isolated instance, then the choice of flow meter needs to be re-evaluated to find a flow-meter with a more appropriate range of flow-rates.

Changes could be made to the parameter reporting section of the firmware so that only parameters that have changed are reported. This would reduce data use which would allow the parameters to be reported more frequently. If the current system of embedding the command in the acknowledgement to the data packet were retained this would decrease the command response time.

Finally, a method of compensating for the non-linearity of the current measurement needs to be found. Currently the maximum average accuracy is 96%.

5.3.2 Control

Use should be made of the EWH model to determine the rate at which the hot and cold water in an EWH mix. This information can be used to explore the possibility of implementing an intelligent control system based on usage volume not internal temperature.

Even if the internal temperature is known accurately the required heating time can not be accurately determined without knowledge of the volume of water to be heated. Similarly if the volume of hot water that has been used is known and very little mixing of hot and cold water has occurred within the EWH the control system can can be set to heat the water when a predetermined percentage of the total hot water within the EWH has been used.

This method of control will shift the typical power use times of the EWH away from the morning and evening peaks as seen in the load profile at present.

If the study is continued it is suggested that users be informed that should communication with the EWH controller fail it can be reset by power cycling the EWH.

5.3.3 Remote

Despite the success of the communications protocol that was used, it is recommended that it be replaced with a protocol that allows direct addressing of the modems. This would allow commands to be sent to the EWH controller asynchronously. While not as important for an EWH controller faster response times will be required if the hardware were adapted to control other systems.

Using the modem to reset the processor by SMS should be investigated a means of error recovery that can be initiated remotely by the persons conducting the study. It is both intrusive and inconvenient to contact a user and ask them to do this manually by power cycling the EWH.

A web based application should be developed to streamline feedback and control. A web based application will be independent of platform, and thus usable on any smart-phone with internet access.

5.3.4 Risk management

To reduce risk associated with the installation of flow meters and valves, non-invasive flow metes should be investigated as a possible substitute. A clip on sonic flow meter or acoustic flow meter would greatly reduce installation time and reduce the risk associated with altering a user's plumbing.

The behaviour of EWHs before they fail should be investigated. If they are found to leak slowly for a period before complete failure the control valve could be removed and instead the EWH would deactivate the element until the EWH has been inspected or replaced.

This would force the user to take action and not ignore the potential problem until it is too late. For this method of risk prevention to work the drip sensor will have to be foolproof. The inconvenience can be offset slightly by integrating the user's plumber of choice into the web application. This way when the user is informed of the leak they can be immediately be provided with a number to call and an estimated quote.

It is recommended that the drip sensor be constructed from a material that will not corrode over time. Successful preliminary experiments have been carried out using stainless steel probes. The sensor can also be redesigned for more rapid installation in a form more suited to the application.

To further aid installation a more standard means of placing the controller needs to be determined. At present the enclosure is attached to the nearest roof truss. This is not ideal because the relative position of the nearest roof truss to the EWH is not constant. This means that sensor and power cable lengths cannot be standardized.

Possible attachment points for the EWH controller enclosure could be the faceplate of the EWH itself or attached to the body of the EWH with bands.

A method of determining the state of the latching valve should be found. Failing that, firmware should be written that will only reactivate power supply to the element after a closed valve has been opened once water flow through the EWH has been detected.

The inclusion of a hardware watchdog to intervene if the controller becomes unresponsive should be investigated.

Finally, the power connections should be redesigned so that all electrical connections are made inside the drip-proof enclosure of the controller onto clearly labelled and robust connectors.

5.4 Future work

There are plans for a large-scale study using the MkIII controller that was designed on this project. In this study the controller will be installed in 300 homes with the goal of reducing energy and water consumption through feedback and intelligent control. This study will begin in the second half of 2016.

The web-based smart-phone application that will be provided as a user interface to the controller is planned to be completed in time for the large scale study.

Data analysis methods are being tested for suitability on the existing database before the data from the large-scale study becomes available.

Finally the recommendations made in this paper will be used to refine further designs of the controller.

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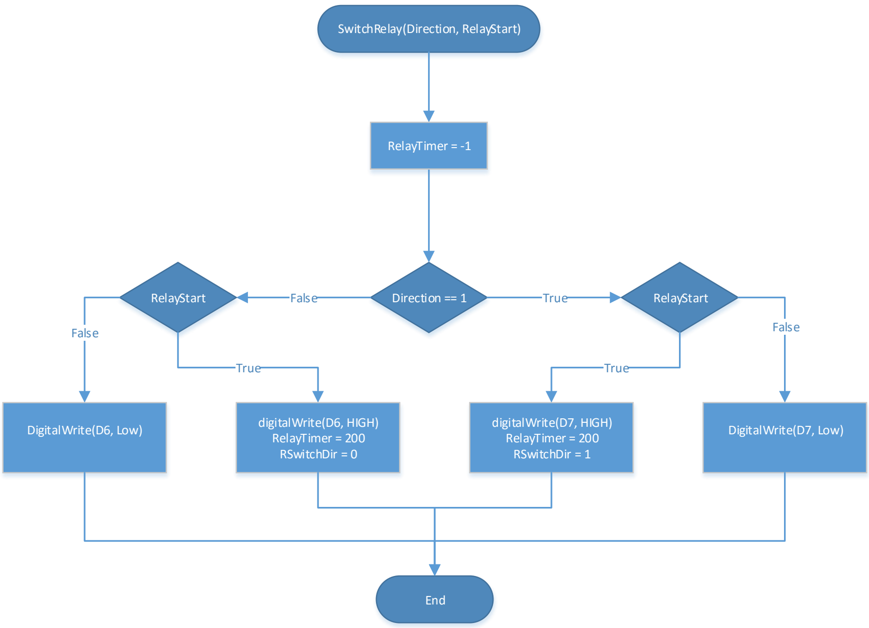
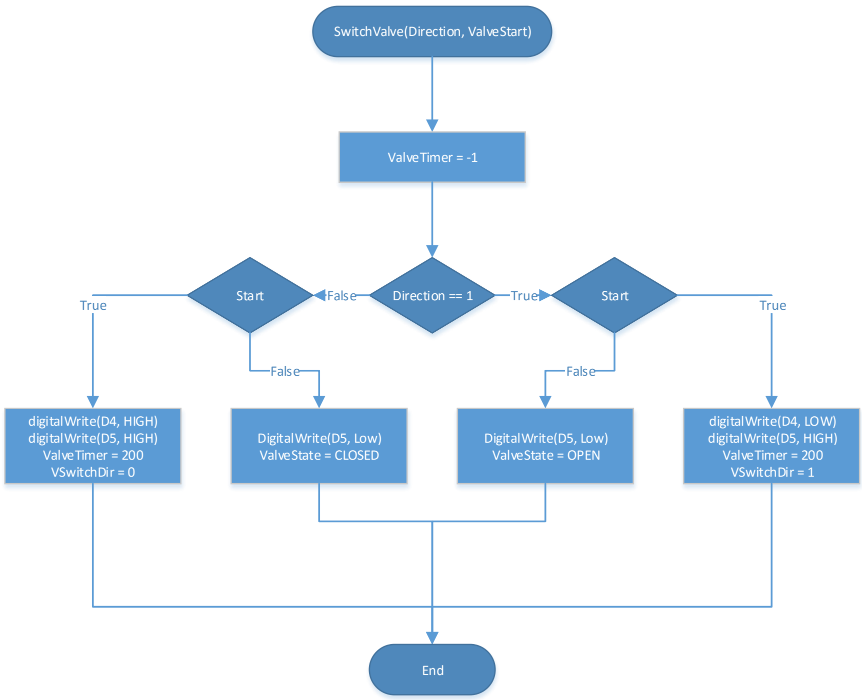
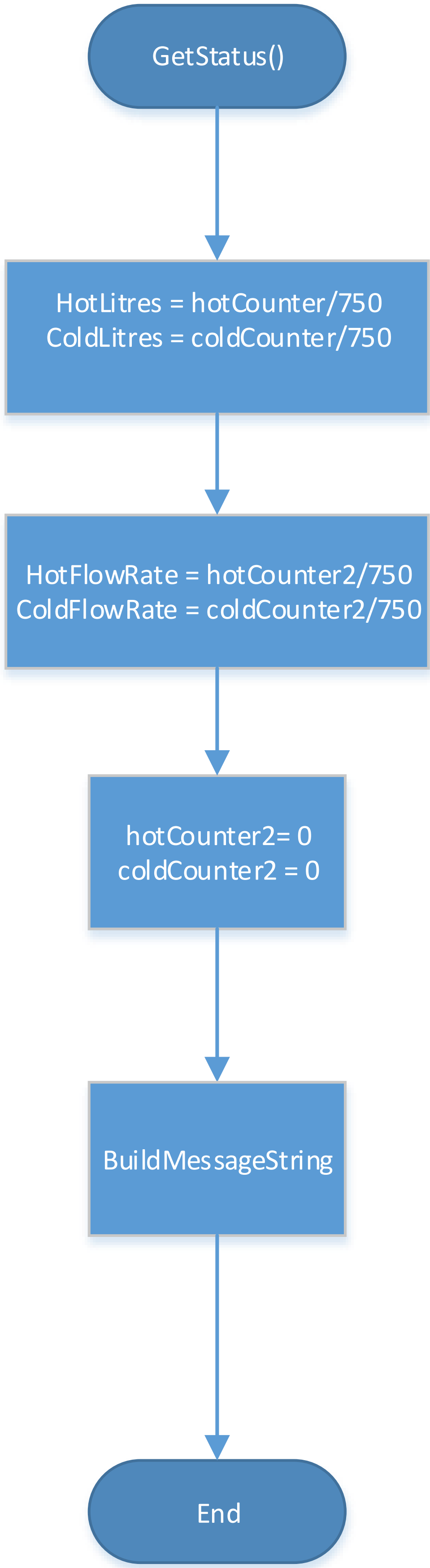
Appendices

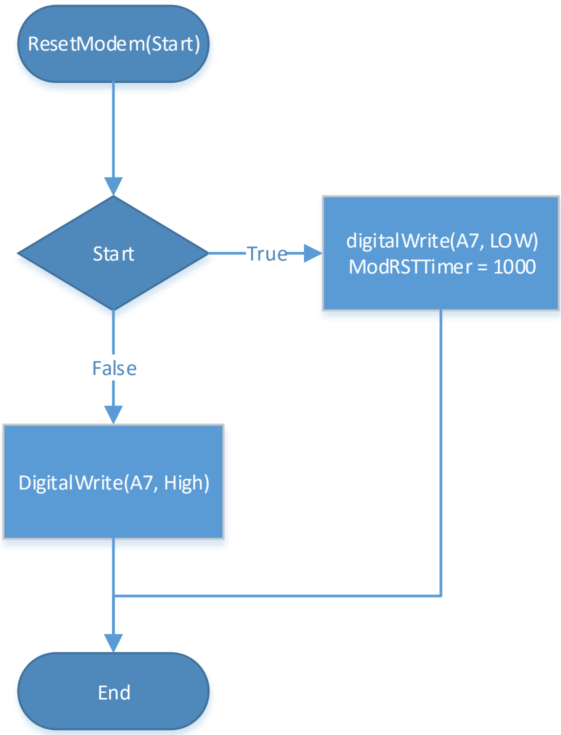
Appendix A

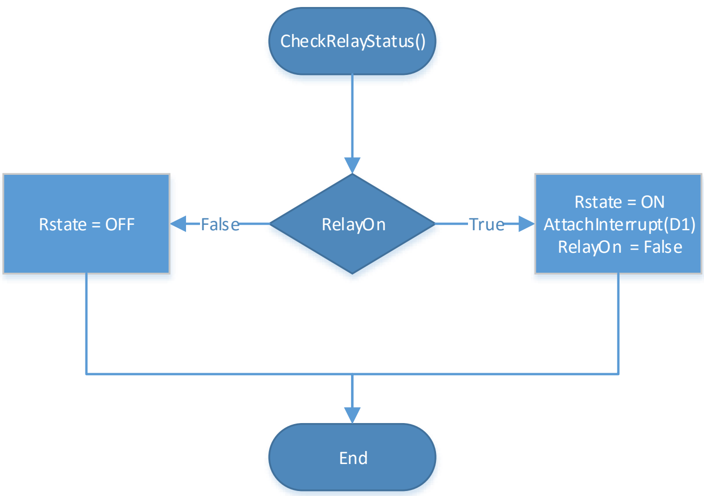
Firmware V2 Flow diagrams

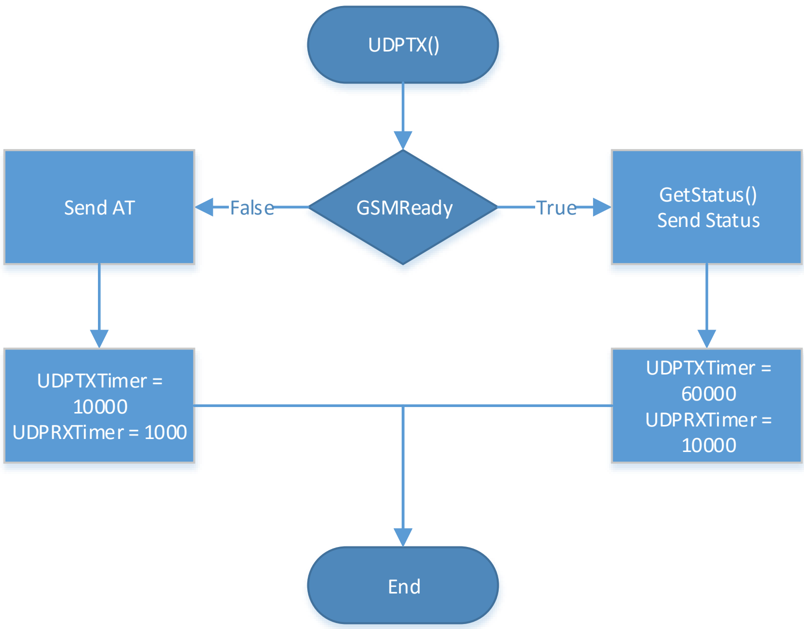


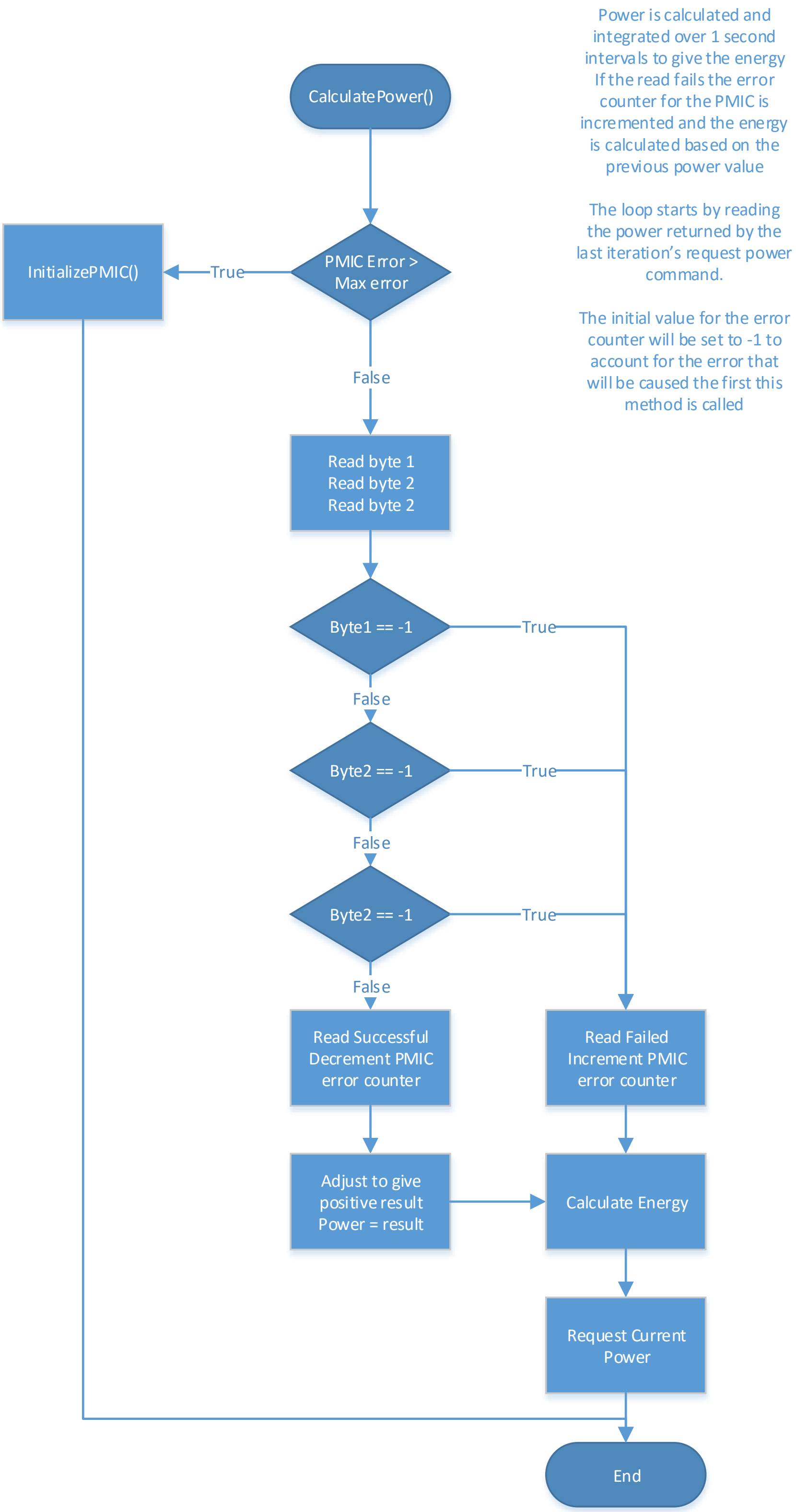

SwitchValve(Direction, ValveStart)
ValveTimer = -1
Direction == 1
True
False
Start
Start
True
False
False
True
digitalWrite(D4, HIGH)
digitalWrite(D5, HIGH)
ValveTimer = 200
VSwitchDir = 0
DigitalWrite(D5, Low)
ValveState = CLOSED
DigitalWrite(D5, Low)
ValveState = OPEN
digitalWrite(D4, LOW)
digitalWrite(D5, HIGH)
ValveTimer = 200
VSwitchDir = 1
End

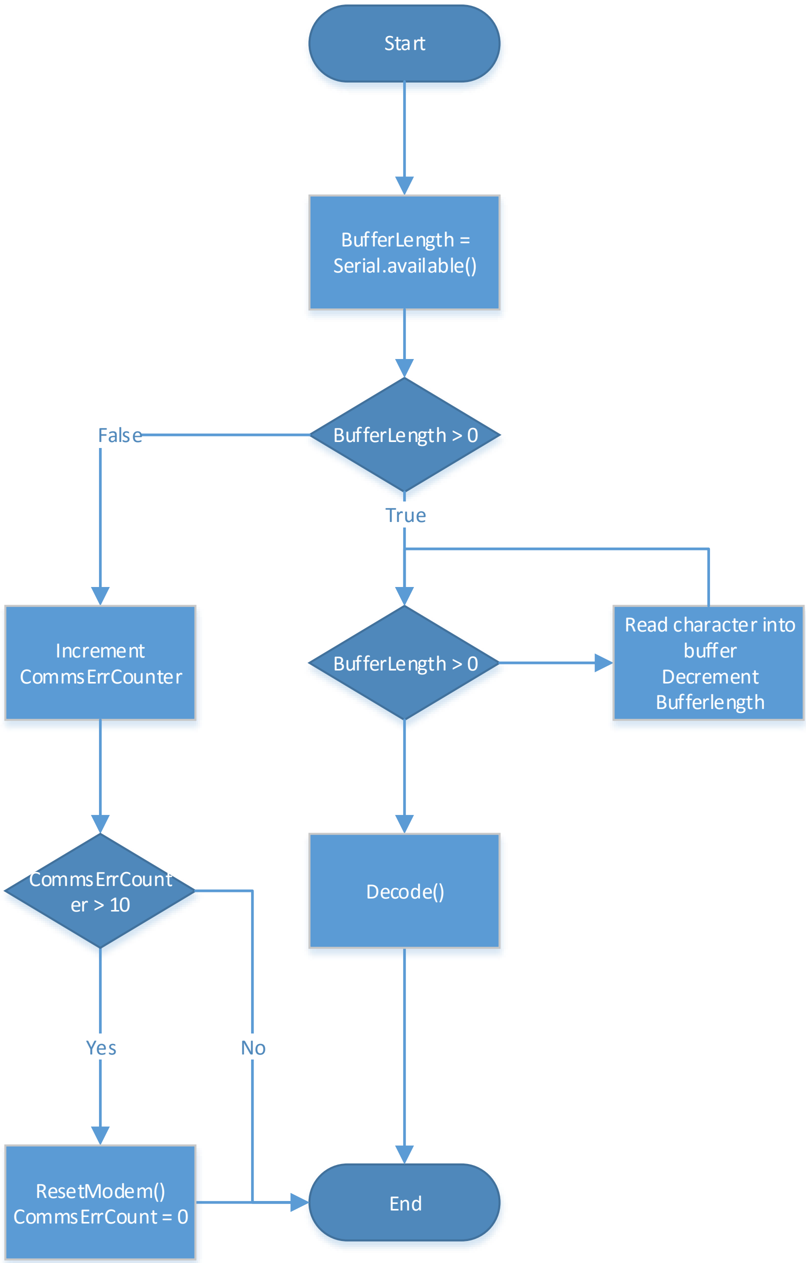

GetStatus()
HotLitres = hotCounter/750
ColdLitres = coldCounter/750
HotFlowRate = hotCounter2/750
ColdFlowRate = coldCounter2/750
hotCounter2= 0
coldCounter2 = 0
BuildMessageString
End

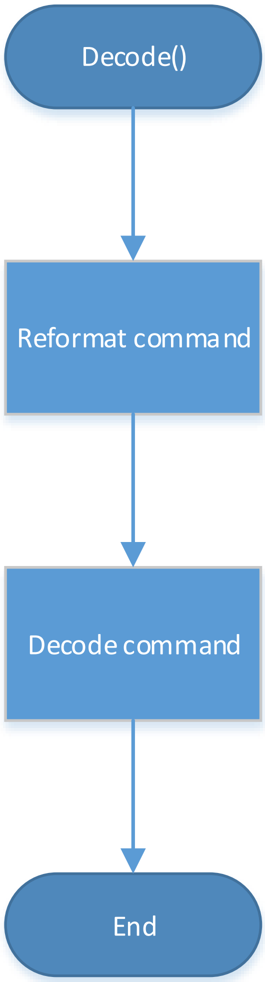

ResetModem(Start)
Start
True
digitalWrite(A7, LOW)
ModRSTTimer = 1000
False
DigitalWrite(A7, High)
End

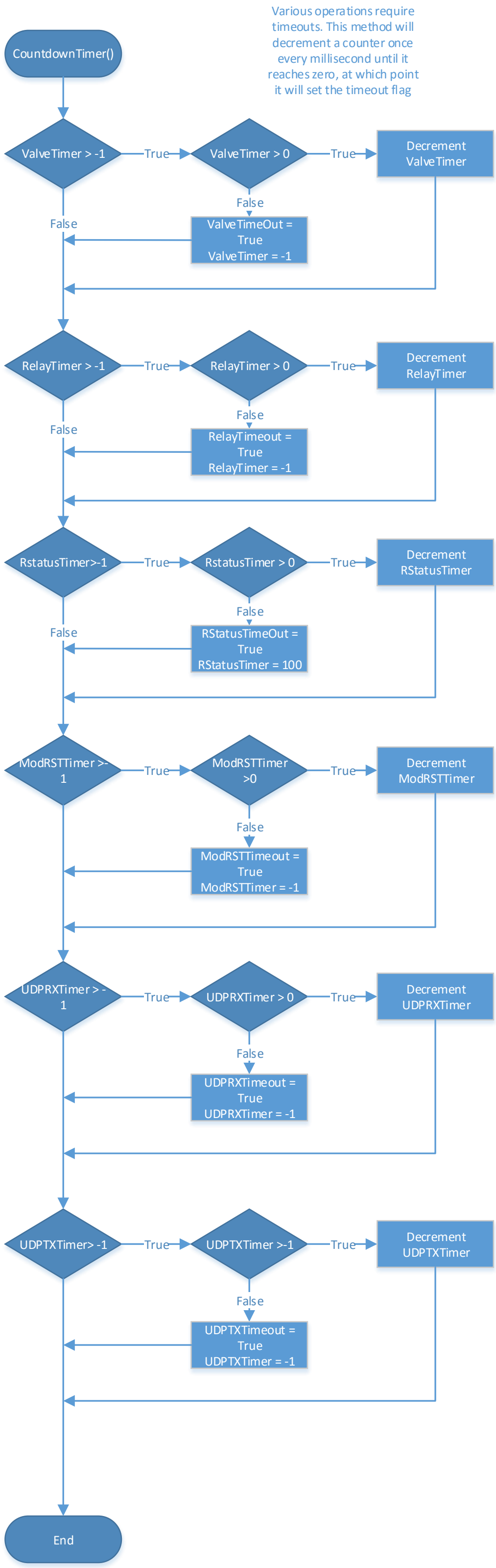

CheckRelayStatus()
Rstate = OFF
False
RelayOn
True
Rstate = ON
AttachInterrupt(D1)
RelayOn = False
End

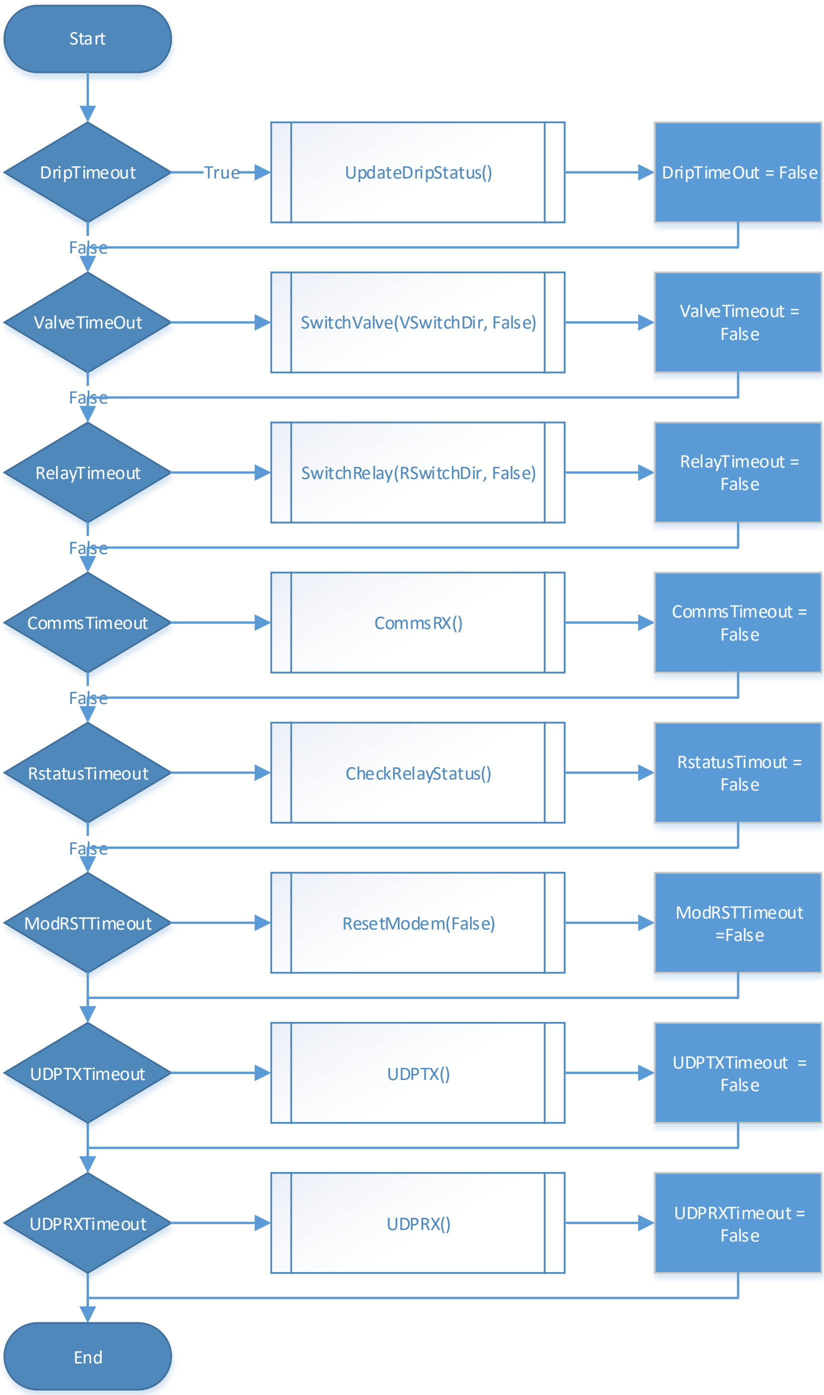

UDPTX()
GSMReady
False
True
Send AT
GetStatus()
Send Status
UDPTXTimer = 10000
UDPRXTimer = 1000
UDPTXTimer = 60000
UDPRXTimer = 10000
End


Power is calculated and integrated over 1 second intervals to give the energy If the read fails the error counter for the PMIC is incremented and the energy is calculated based on the previous power value
The loop starts by reading the power returned by the last iteration's request power command.
The initial value for the error counter will be set to -1 to account for the error that will be caused the first this method is called
CalculatePower()
PMIC Error > Max error
True
InitializePMIC()
False
Read byte 1
Read byte 2
Read byte 2
Byte1 == -1
Byte2 == -1
Byte2 == -1
Read Successful Decrement PMIC error counter
Read Failed Increment PMIC error counter
Adjust to give positive result Power = result
Calculate Energy
Request Current Power
End

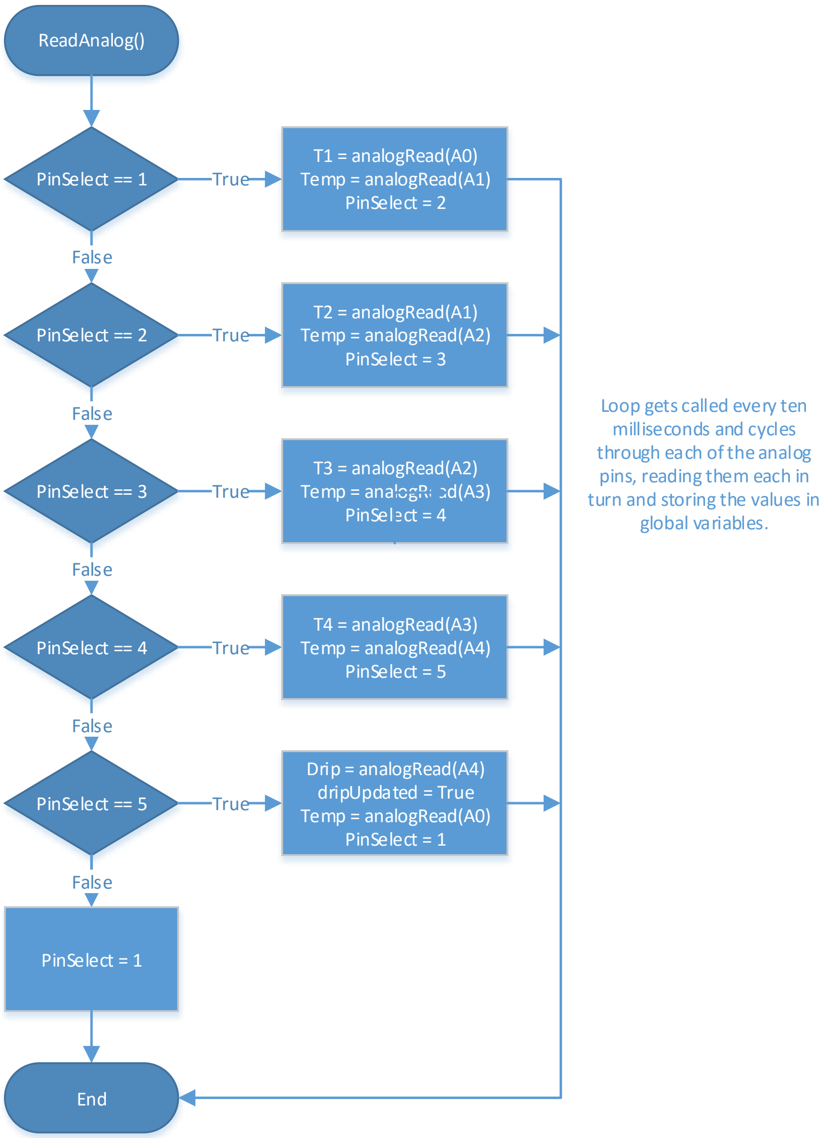

Start
BufferLength =
Serial.available()
BufferLength > 0
False
True
Increment
CommsErrCounter
BufferLength > 0
Read character into
buffer
Decrement
Bufferlength
CommsErrCount
er > 10
Decode()
Yes
No
ResetModem()
CommsErrCount = 0
End

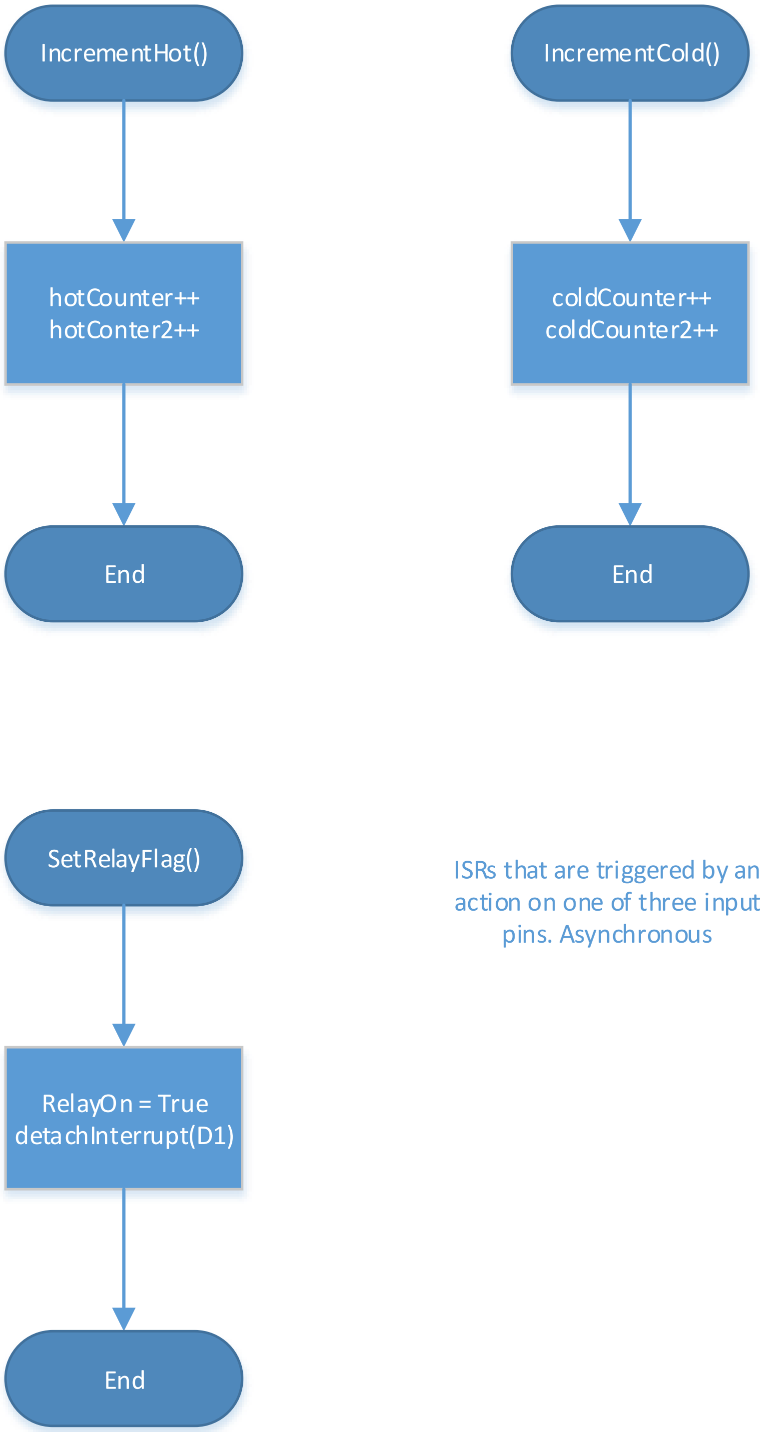

Decode()
Reformat command
Decode command
End

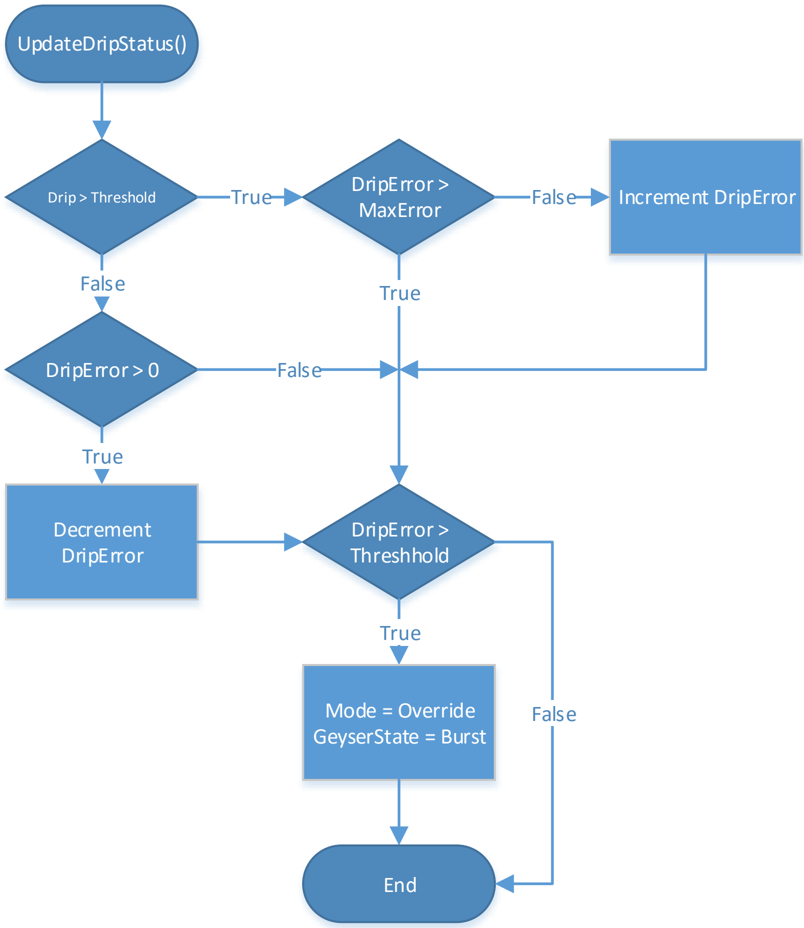

Various operations require timeouts. This method will decrement a counter once every millisecond until it reaches zero, at which point it will set the timeout flag
CountdownTimer()
ValveTimer > -1
True
ValveTimer > 0
True
Decrement ValveTimer
False
False
ValveTimeOut = True ValveTimer = -1
RelayTimer > -1
RelayTimer > 0
Decrement RelayTimer
RelayTimeout = True RelayTimer = -1
RstatusTimer>-1
RstatusTimer > 0
Decrement RStatusTimer
RStatusTimeOut = True RStatusTimer = 100
ModRSTTimer >-1
ModRSTTimer >0
Decrement ModRSTTimer
ModRSTTimeout = True ModRSTTimer = -1
UDPRXTimer > -1
UDPRXTimer > 0
Decrement UDPRXTimer
UDPRXTimeout = True UDPRXTimer = -1
UDPTXTimer> -1
UDPTXTimer >-1
Decrement UDPTXTimer
UDPTXTimeout = True UDPTXTimer = -1
End



Start
DripTimeout
True
UpdateDripStatus()
DripTimeOut = False
False
ValveTimeOut
SwitchValve(VSwitchDir, False)
ValveTimeout = False
False
RelayTimeout
SwitchRelay(RSwitchDir, False)
RelayTimeout = False
False
CommsTimeout
CommsRX()
CommsTimeout = False
False
RstatusTimeout
CheckRelayStatus()
RstatusTimout = False
False
ModRSTTimeout
ResetModem(False)
ModRSTTimeout =False
UDPTXTimeout
UDPTX()
UDPTXTimeout = False
UDPRXTimeout
UDPRX()
UDPRXTimeout = False
End


ReadAnalog()
PinSelect == 1
True
T1 = analogRead(A0)
Temp = analogRead(A1)
PinSelect = 2
False
PinSelect == 2
True
T2 = analogRead(A1)
Temp = analogRead(A2)
PinSelect = 3
False
PinSelect == 3
True
T3 = analogRead(A2)
Temp = analogRead(A3)
PinSelect = 4
False
PinSelect == 4
True
T4 = analogRead(A3)
Temp = analogRead(A4)
PinSelect = 5
False
PinSelect == 5
True
Drip = analogRead(A4)
dripUpdated = True
Temp = analogRead(A0)
PinSelect = 1
False
PinSelect = 1
End
Loop gets called every ten milliseconds and cycles through each of the analog pins, reading them each in turn and storing the values in global variables.


IncrementHot()
hotCounter++
hotConter2++
End
IncrementCold()
coldCounter++
coldCounter2++
End
SetRelayFlag()
RelayOn = True
detachInterrupt(D1)
End
ISRs that are triggered by an action on one of three input pins. Asynchronous


UpdateDripStatus()
Drip > Threshold
True
DripError > MaxError
False
Increment DripError
False
True
DripError > 0
False
True
Decrement DripError
DripError > Threshold
True
Mode = Override
GeyserState = Burst
False
End